

6 Integrated Management Practices

IN THIS CHAPTER...

Specifications for:

- *Bioretention areas*
- *Amending construction site soils*
- *Permeable paving*
- *Vegetated roofs*
- *Minimal excavation foundations*
- *Roof rainwater collection systems*

Integrated management practices (IMPs) are the tools used in a low impact development (LID) project for water quality treatment and flow control. The term IMP is used instead of best management practice or BMP (used in a conventional development) because the controls are integrated throughout the project and provide a landscape amenity in the LID design.

6.1 Bioretention Areas

The bioretention concept originated in Prince George's County, Maryland in the early 1990s and is a principal tool for applying the LID design approach. The term bioretention was created to describe an integrated stormwater management practice that uses the chemical, biological, and physical properties of plants, microbes, and soils to remove, or retain, pollutants from stormwater runoff. Numerous designs have evolved from the original application; however, there are fundamental design characteristics that define bioretention across various settings.

Bioretention areas (also known as rain gardens) are:

- Shallow landscaped depressions with a designed soil mix and plants adapted to the local climate and soil moisture conditions that receive stormwater from a small contributing area.
- Facilities designed to more closely mimic natural conditions, where healthy soil structure and vegetation promote the infiltration, storage, and slow release of stormwater flows.
- Small-scale, dispersed facilities that are integrated into the site as a landscape amenity.
- An IMP designed as part of a larger LID approach. Bioretention can be used as a stand-alone practice on an individual lot, for example; however, best performance is achieved when integrated with other LID practices.

Bioretention is an integrated stormwater management practice that uses the chemical, biological, and physical properties of plants, microbes, and soils to remove, or retain, pollutants from stormwater.

The term bioretention is used to describe various designs using soil and plant complexes to manage stormwater. The following terminology is used in this manual:

- **Bioretention cells:** Shallow depressions with a designed planting soil mix and a variety of plant material, including trees, shrubs, grasses, and/or other herbaceous plants. Bioretention cells may or may not have an under-drain and are not designed as a conveyance system.

- **Bioretention swales:** Incorporate the same design features as bioretention cells; however, bioretention swales are designed as part of a conveyance system and have relatively gentle side slopes and flow depths that are generally less than 12 inches.
- **Biodetention:** A design that uses vegetative barriers arranged in hedgerows across a slope to disperse, infiltrate, and treat stormwater (see sloped biodetention description in this chapter).

The following section outlines various applications and general design guidelines, as well as specifications, for individual bioretention components. Design examples are also included in Appendix 2 to provide designers with a pool of concepts and specifications useful for developing bioretention facilities specific to local needs. This section draws information from numerous sources; however, many of the specifications and guidelines are from extensive work and experience developed in Prince George's County, Maryland and the city of Seattle.

6.1.1 Applications

While the original concept of bioretention focused on stormwater pollutant removal, the practice is also used for water quantity control. Where the surrounding native soils have adequate infiltration rates, bioretention can be used as a retention facility. Under-drain systems can be installed and the facility used to filter pollutants and detain flows that exceed infiltration capacity of the surrounding soil. However, designs utilizing under-drains provide less flow control benefits.

Rain gardens are a landscape amenity and a stormwater control practice that can be applied in various settings, including:

- Individual lots for rooftop, driveway, and other on-lot impervious surface infiltration.
- Shared facilities located in common areas for individual lots.
- Areas within loop roads or cul-de-sacs.
- Landscaped parking lot islands.
- Within right-of-ways along roads (linear bioretention swales and cells).
- Common landscaped areas in apartment complexes or other multifamily housing designs.

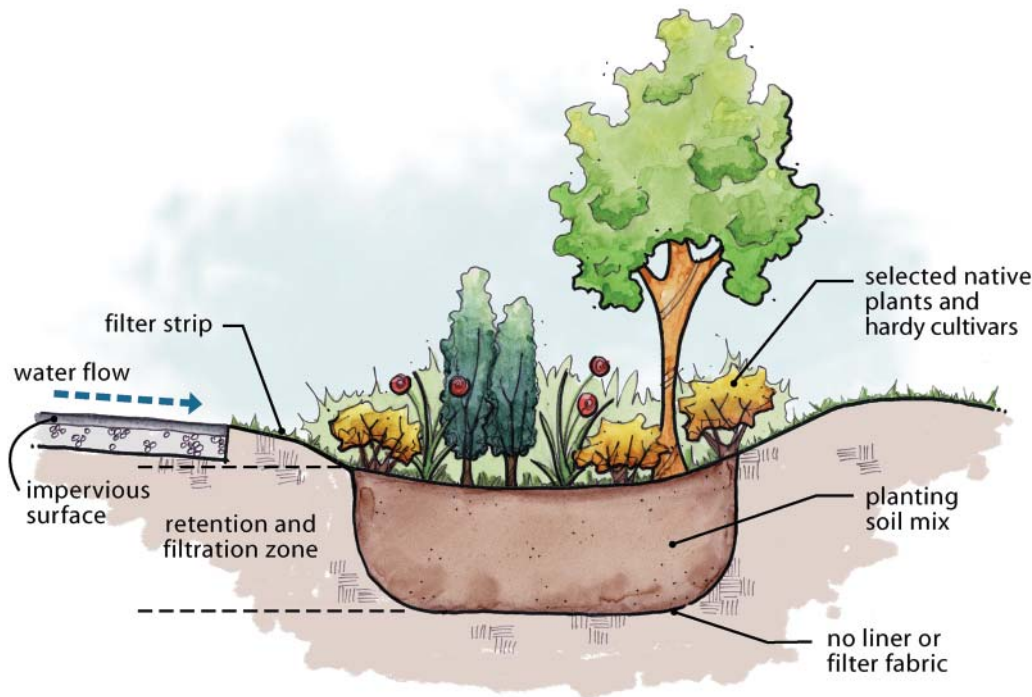
Figure 6.1.1 Bioretention area in center of apartment building courtyard, Portland, Oregon.

Photo by Curtis Hinman



Figure 6.1.2 Cross-section of a basic bioretention cell with no under-drain.

Graphic by AHBL Engineering



6.1.2 Design

Bioretention systems are placed in a variety of residential and commercial settings, and are a visible and accessible component of the site. Design objectives and site context are, therefore, important factors for successful application.

The central design considerations include:

- *Soils:* The soils underlying and surrounding bioretention facilities are a principal design element for determining infiltration capacity, sizing, and rain garden type. The planting soil placed in the cell or swale is highly permeable and high in organic matter (e.g., loamy sand, USDA soil texture classification, mixed thoroughly with compost amendment) and a surface mulch layer. See Section 6.1.2.3: Bioretention Components for details.
- *Site topography:* For slopes greater than 10 percent, sloped bioretention and weep garden designs can be used. See Section 6.1.2.1: Types of bioretention areas.
- *Depth-to-water table:*
 - o A minimum separation of 1 foot from the seasonal high water mark to the bottom of the bioretention area is recommended where the contributing area of the bioretention has less than 5,000 square feet of pollution-generating impervious surface; and less than 10,000 square feet of impervious surface; and less than $\frac{3}{4}$ acres of lawn. Recommended separation distances for bioretention areas with small contributing areas are less than the new Department of Ecology (Ecology) recommendation of 3 feet for two reasons: (1) bioretention soil mixes provide effective pollutant capture; and (2) hydrologic loading and potential for groundwater mounding is reduced when managing flows from small contributing areas.
 - o A minimum separation of 3 feet from the seasonal high water mark to the bottom of the bioretention area is recommended where the contributing

area of the bioretention area is equal to or exceeds any of the following limitations: 5,000 square feet of pollution-generating impervious surface; or 10,000 square feet of impervious surface; or $\frac{3}{4}$ acres of lawn and landscape. See Bioretention Areas in Chapter 7 for flow modeling guidance.

- *Expected pollutant loading:* See sections 6.1.2.3: Bioretention components and 6.1.4: Performance for recommended designs by pollutant type.
- *Site growing characteristics and plant selection:* Appropriate plants should be selected for sun exposure, soil moisture, and adjacent plant communities. Invasive species control may also be necessary.
- *Transportation safety:* The design configuration and selected plant types should provide adequate sight distances, clear spaces, and appropriate setbacks for roadway applications.
- *Visual buffering:* Bioretention facilities can be used to buffer structures from roads, enhance privacy among residences, and for an aesthetic site feature.
- *Ponding depth and surface water draw-down:* Flow control needs, as well as location in the development, will determine draw-down timing. For example, front yards and entrances to residential or commercial developments may require rapid surface dewatering for aesthetics. See Section 6.1.2.3: Bioretention components for details.
- *Impacts of surrounding activities:* Human activity influences the location of the facility in the development. For example, locate bioretention areas away from traveled areas on individual lots to prevent soil compaction and damage to vegetation, and provide barriers to restrict vehicle access in roadside applications.
- *Setbacks:* Local jurisdiction guidelines should be consulted for appropriate bioretention area setbacks from wellheads, on-site sewage systems, basements, foundations, and utilities.

6.1.2.1 Types of bioretention areas

Numerous designs have evolved from the original bioretention concept as designers have adopted the practice to different physical settings. Types of bioretention designs include:

- Bioretention cells integrated into gardens on individual lots.

Figure 6.1.3 Bioretention cell integrated into landscaping.

Photo by Larry Coffman



- Curb or curbless bioretention in landscaped parking lot islands.



Figure 6.1.4 Bioretention landscaped island with curb cut to allow flows to enter.
Photo by Larry Coffman

- **Off-line bioretention** areas (Figure 6.1.5) are placed next to a swale with a common flow entrance and flow exit, and the bioretention invert placed below the swale **invert** to provide the proper ponding depth (often 6 to 12 inches).



Figure 6.1.5 (left) Off-line bioretention area adjacent to roadside swale.
Photo by Larry Coffman

Figure 6.1.6 (right) Bioretention swale in Seattle.
Photo courtesy of Seattle Public Utilities

- **In-line bioretention** swales are hybrid facilities usually installed along roadways that incorporate bioretention cell and swale characteristics (see Figure 6.1.6 and Appendix 2: Bioretention Examples for design details).
- Sloped or weep garden bioretention areas (Figure 6.1.7) are used for steeper gradients where a retaining wall is used for structural support and for allowing storm flows, directed to the facility, to seep out.
- Sloped bioretention-use vegetative barriers, designed for a specific hydraulic capacity, placed along slope contours (see Figure 6.1.8 and Appendix 2: Bioretention Examples for design details).

Figure 6.1.7 Sloped or weep garden bioretention area.

Photo courtesy of LID Center



Figure 6.1.8 Sloped bioretention area.

Photo courtesy of Murphee Engineering



- Tree box filters are street tree plantings with an enlarged planting pit for additional storage, a storm flow inlet from the street or sidewalk, and an under-drain system.

Figure 6.1.9 Tree box filter.

Photo by Puget Sound Action Team



6.1.2.2 Determining infiltration rates

Infiltration rates are necessary to determine flow reduction benefits for bioretention areas when using the Western Washington Hydrologic Model (WWHM) or MGS Flood. See Figure 6.1.10 for a graphic representation of the process to determine infiltration rates.

The assumed infiltration rate for determining the flow reduction benefits of bioretention areas should be the lower of the estimated long-term rate of the planting soil mix or the initial (short-termed or measured) infiltration rate of the underlying soil profile. The overlying planting soil mix protects the underlying native soil from sedimentation; accordingly, the underlying soil does not require a correction factor. See Chapter 7 for more detail on flow control modeling for bioretention areas.

The following provides recommended tests for the soils underlying and planting soil mixes within bioretention areas.

1. Underlying native soils:

- Method 1: Use Table 3.7 of the Ecology 2005 *Stormwater Management Manual for Western Washington* (SMMWW) to determine the short-term infiltration rate of the underlying soil. Soils not listed in the table cannot use this approach. Use 1 as the infiltration reduction factor.
- Method 2: Determine the D_{10} size of the underlying soil. Use the upperbound line in Figure 4-17 of the Washington State Department of Transportation (WSDOT) 2004 *Highway Runoff Manual* to determine the corresponding infiltration rate. Use 1 as the infiltration reduction factor.
- See the 2005 SMMWW Volume III for details on methods 1 and 2.
- Method 3: Field infiltration tests (the specific test depends on scale of the project).
 - o Small bioretention cells (bioretention facilities receiving water from 1 or 2 individual lots or < 1/4 acre of pavement or other impervious surface): Small-scale infiltration tests such as the U.S. Environmental Protection Agency (USEPA Falling Head or double ring infiltrometer tests, ASTM 3385-88). Small-scale infiltration tests, such as a double ring infiltrometer, may not adequately measure variability of conditions in test areas and, if used, measurements should be taken at several locations within the area of interest. Soil pit excavation may still be necessary if highly variable soil conditions or seasonal high water tables are suspected. Use 1 as an infiltration correction factor.
 - o Large bioretention cells (bioretention facilities receiving water from several lots or 1/4 to 1/2-acre of pavement or other impervious surface): Pilot Infiltration Test (PIT) or small-scale test infiltration pits (septic test pits) at a rate of 1 pit/cell excavated to a depth of at least 5 feet and preferably 6 to 8 feet. See 2005 SMMWW Appendix III-D (formerly V-B) for PIT method description. Use 1 as an infiltration correction factor.
 - o Bioretention swales: approximately 1 pit/50 feet of swale to a depth of at least 5 feet (personal communication, Larry West, Ed O'Brien, 2004).
 - o Consult a geotechnical engineer for site-specific analysis recommendations.
- Use the measured infiltration rate of the underlying native soil as the assumed infiltration rate of the bioretention area if it is lower than the planting soil mix.

2. Compost-amended planting mix soils: Depending on the size of contributing area use one of the following two recommended test protocols.

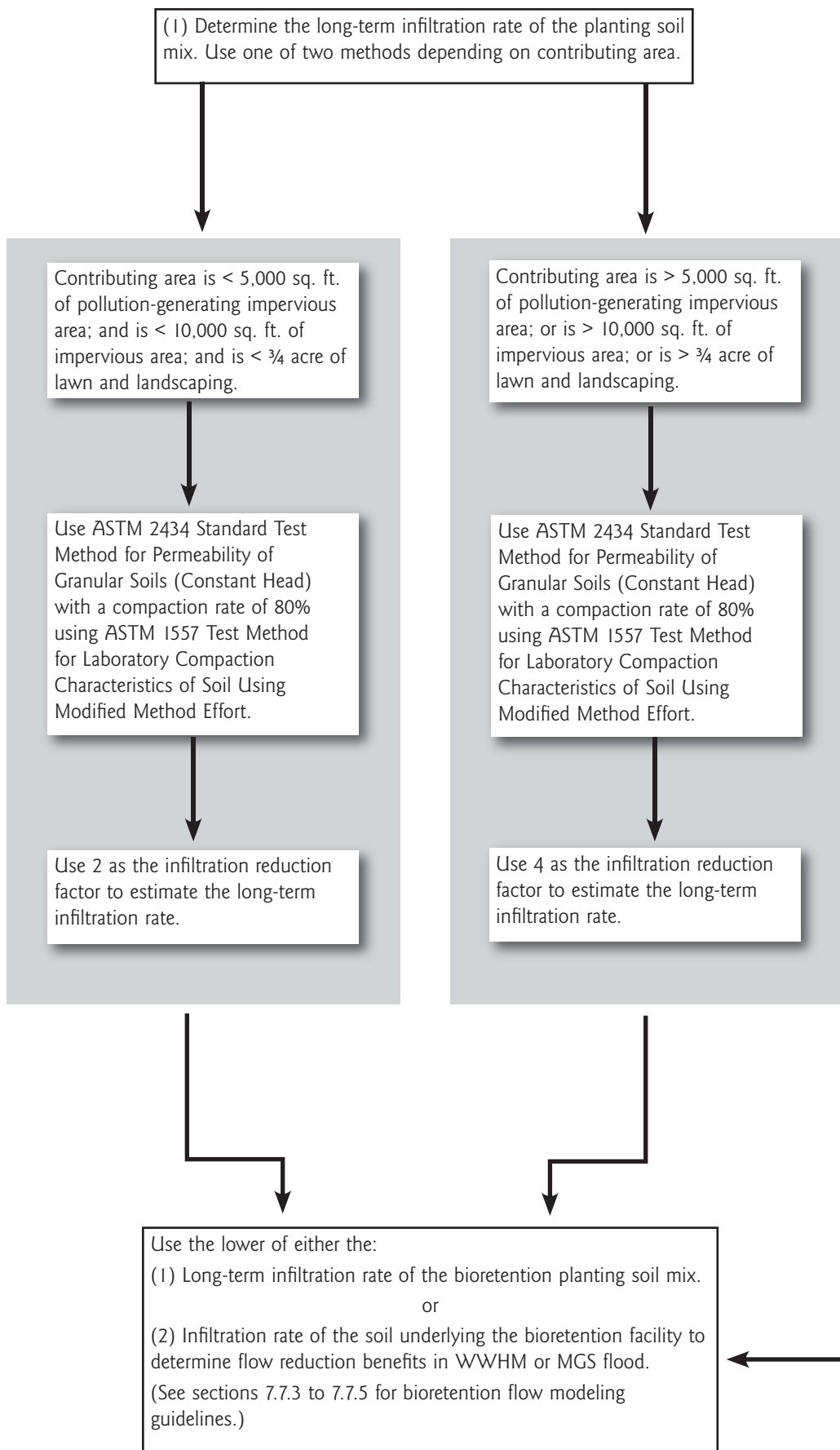
Flow Modeling Guidance

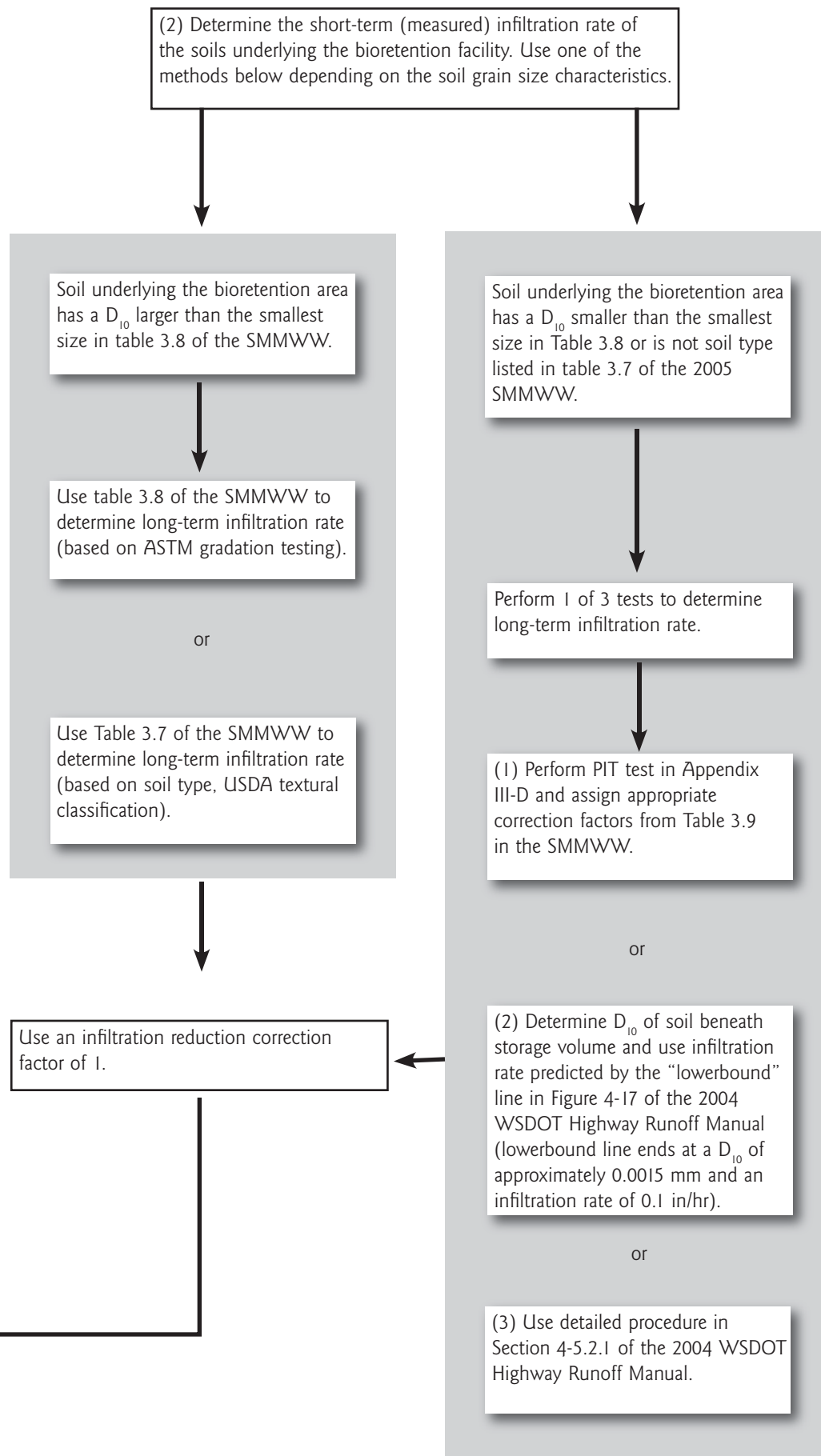
See Chapter 7 for guidelines for applying infiltration rates when using the WWHM to determine flow control credits for bioretention areas.

Figure 6.1.10

Recommendations for determining infiltration rates of soils in bioretention areas.

(See sections 7.7.3 to 7.7.5 for using infiltration rates and bioretention flow modeling guidelines.)





- Test 1: If the contributing area of the bioretention cell or swale has less than 5,000 square feet of pollution-generating impervious surface; and less than 10,000 square feet of impervious surface; and less than $\frac{3}{4}$ acre of lawn and landscape:
 - o Use ASTM D 2434 Standard Test Method for Permeability of granular Soils (Constant Head) with a compaction rate of 80 percent using ASTM D1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.
 - o Use 2 as the infiltration reduction factor.
- Test 2: If the contributing area of the bioretention cell or swale is equal to or exceeds any of the following limitations: 5,000 square feet of pollution-generating impervious surface; or 10,000 square feet of impervious surface; or $\frac{3}{4}$ acre of lawn and landscape:
 - o Use ASTM D 2434 Standard Test Method for Permeability of granular Soils (Constant Head) with a compaction rate of 80 percent using ASTM D1557 Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort.
 - o Use 4 as the infiltration reduction factor.
- Use the long-term infiltration rate of the planting soil mix as the assumed infiltration rate of the bioretention area if it is lower than the underlying native soil.

6.1.2.3 Bioretention components

The following provides a description and suggested specifications for the components of bioretention cells and swales. Some or all of the components may be used for a given application depending on the site characteristics and restrictions, pollutant loading, and design objectives. Also see Appendix 2 for various bioretention design examples.

Pretreatment

Vegetated buffer strips slow incoming flows and provide an initial settling of particulates. Design will depend on topography, flow velocities, volume entering the buffer, and site constraints. Flows entering a rain garden should be less than 1.0 ft/second to minimize erosion potential. Engineered flow dissipation (e.g., rock pad) should be incorporated into curb-cut or piped (concentrated) flow entrances.

Flow entrance

Five primary types of flow entrances can be used for bioretention cells:

- *Dispersed, low velocity flow across a landscape area:* This is the preferred method of delivering flows to the rain garden cell. Dispersed flow may not be possible given space limitations or if the facility is controlling roadway or parking lot flows where curbs are mandatory.
- *Dispersed flow across pavement or gravel and past wheel stops for parking areas.*
- *Curb cuts for roadside or parking lot areas:* Curb cuts should include rock or other erosion protection material in the channel entrance to dissipate energy. Flow entrance should drop 2 to 3 inches from curb line and provide an area for settling and periodic removal of sediment and coarse material before flow dissipates to the remainder of the cell (Prince George's County, Maryland, 2002, and U.S. Army Environmental Center and Fort Lewis, 2003).
- *Pipe flow entrance:* Piped entrances should include rock or other erosion protection material in the channel entrance to dissipate energy and/or flow dispersion.

- *Catch basin:* Catch basins can be used to slowly release water to the bioretention area through a grate for filtering coarse material.

Woody plants can restrict or concentrate flows and can be damaged by erosion around the root ball and should not be placed directly in the entrance flow path (Prince George's County, 2002).



Figure 6.1.11 Bioretention with curb cuts in parking lot islands.

Photo by Larry Coffman

Ponding area

The ponding area provides surface storage for storm flows, particulate settling, and the first stages of pollutant treatment within the cell. Pool depth and draw-down rate are recommended to provide surface storage, adequate infiltration capability, and soil moisture conditions that allow for a range of appropriate plant species (Prince George's County, 2002).

- Maximum ponding depth: 12 inches recommended.
- Surface pool drawdown time: 24 hours recommended.
- Soils must be allowed to dry out periodically in order to:
 - o Restore hydraulic capacity to receive flows from subsequent storms.
 - o Maintain infiltration rates.
 - o Maintain adequate soil oxygen levels for healthy soil biota and vegetation.
 - o Provide proper soil conditions for biodegradation and retention of pollutants. (Ecology, 2001)

Under-drain

The area above an under-drain pipe in a bioretention area provides detention and pollutant filtering; however, only the area below the under-drain invert and the bottom of the bioretention facility can be used in the WWHM for flow control benefit (see Chapter 7 for bioretention area flow control credits). Under-drain systems (see Figure 6.1.12) should be installed only when the bioretention area is:

- Located near sensitive infrastructure (e.g., unsealed basements) and potential for flooding is likely.
- Used for filtering storm flows from gas stations or other pollutant hotspots (requires impermeable liner).
- In soils with infiltration rates that are not adequate to meet maximum pool and system dewater rates.

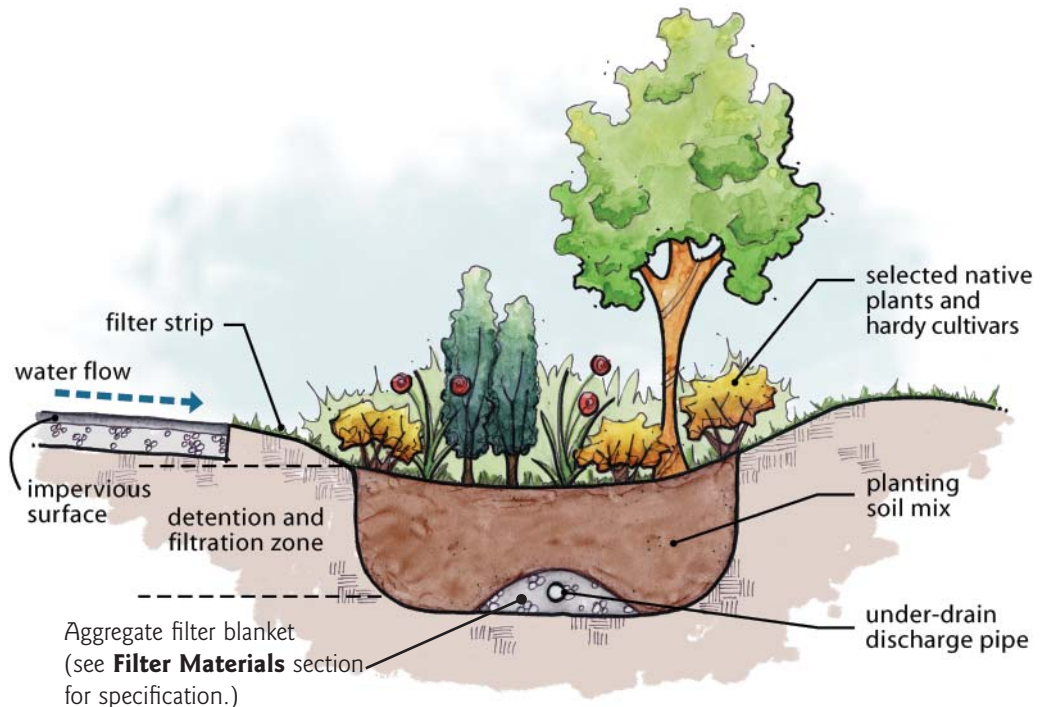
The under-drain can be connected to a downstream open conveyance (bioretention swale), to another bioretention cell as part of a connected treatment system, daylight to a dispersion area using an effective flow dispersion practice, or to a storm drain.

The pipe diameter will depend on hydraulic capacity required (4 to 8 inches is common). The preferred material is slotted 6-inch, thick-walled plastic pipe. The slot opening should be smaller than the smallest aggregate gradation for the gravel blanket to prevent migration of material into the drain. This configuration allows for pressurized water cleaning and root cutting if necessary (personal communication, Tracy Tackett, 2004). Example specification:

- Slotted subsurface drain PVC per ASTM D1785 SCH 40.
- Slots should be cut perpendicular to the long axis of the pipe and be 0.04 to 0.069 inches by 1 inch long and be spaced 0.25 inches apart (spaced longitudinally). Slots should be arranged in four rows spaced on 45-degree centers and cover $\frac{1}{2}$ of the circumference of the pipe. See Filter Materials section for aggregate gradation appropriate for this slot size.

Figure 6.1.12 Bioretention with under-drain.

Graphic by AHBL Engineering

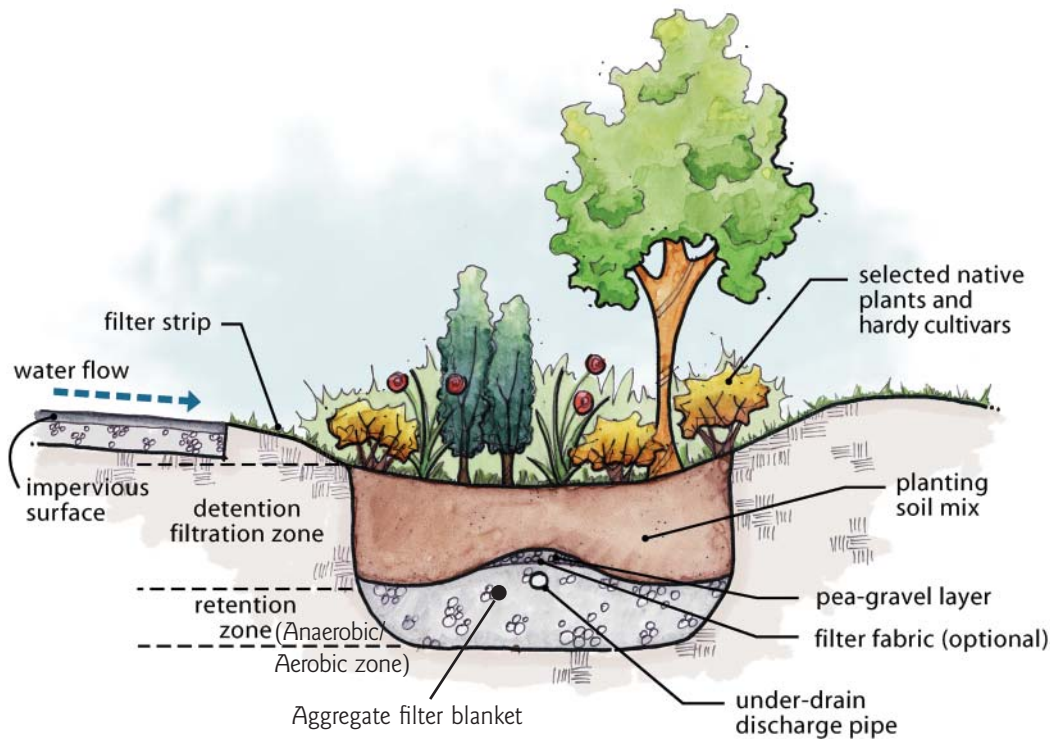


Perforated PVC or flexible slotted HDPE pipe can be used; however, cleaning operations, if necessary, can be more difficult or not possible. Under-drains should be sloped at a minimum of 0.5 percent unless otherwise specified by an engineer (Low Impact Development Center, 2004). Wrapping the under-drain pipe in filter fabric increases chances of clogging and is not recommended (Low Impact Development Center, 2004). A 6-inch rigid non-perforated observation pipe or other maintenance access should be connected to the under-drain every 250 to 300 feet to provide a clean-out port, as well as an observation well to monitor dewatering rates (Prince George's County, 2002 and personal communication, Tracey Tackett, 2004).

Bioretention areas do not effectively remove nitrate. Where nitrate is a concern, the under-drain can be elevated from the bottom of the bioretention facility and within the gravel blanket to create a fluctuating anaerobic/aerobic zone below the drain pipe (Figure 6.1.13). **Denitrification** within the anaerobic zone is facilitated by microbes using forms of nitrogen (NO_2 and NO_3) instead of oxygen for respiration. Adding a suitable carbon source (e.g., wood chips) to the gravel layer provides a nutrition source for the microbes, enables anaerobic respiration, and can enhance the denitrification process (Kim, Seagren and Davis, 2003).

Figure 6.1.13 Bioretention with elevated under-drain.

Graphic by AHBL Engineering



Filter materials

Gravel blankets and filter fabrics buffer the under-drain system from sediment input and clogging. Properly selected for the soil gradation, geosynthetic filter fabrics can provide adequate protection from the migration of fines. Aggregate filter blankets, with proper gradations, provide a larger surface area for protecting under-drains and are preferred.

Suggested specifications for filter materials include:

1. For use with heavy walled slotted pipe (see under-drain specification above):

- Type 26 mineral aggregate (gravel backfill for drains, city of Seattle)

Sieve size	Percent Passing
¾ inch	100
¼ inch	30-60
US No. 8	20-50
US No. 50	3-12
US No. 200	0-1

- Place under-drain on a 3-foot wide bed of the Type 26 aggregate at a minimum thickness of 6 inches and cover with Type 26 aggregate to provide a 1-foot minimum depth around the top and sides of the slotted pipe.
2. If proper gradation and/or slotted pipe are not available and perforated PVC or flexible HDPE pipe is used:
 - The under-drain pipe should be placed on a 3-foot wide bed of ½ to 1½-inch drain rock (ASTM No. 57 aggregate or equivalent) at a minimum thickness of 3 inches, and covered with 6 inches of No. 57 aggregate.

Double-washed stone is preferred to reduce suspended solids and potential for clogging (Low Impact Development Center, 2004).

- If filter fabric is used, use a non-woven material placed over the drain rock and extending 2 feet on either side of the under-drain. Wrapping the gravel blanket in filter fabric can cause premature failure due to clogging and is not recommended (Prince George's County, 2002).
- A pea gravel diaphragm (with or without a filter fabric) reduces the likelihood of clogging when used with drain rock. Use ¼ to ½-inch diameter double-washed gravel (ASTM D 448 or equivalent) placed over the drain rock to a thickness of 3 to 8 inches (Prince George's County, 2002). If filter fabric is used, place between the drain rock and pea gravel extending 2 feet on either side of the under-drain. The strip of filter fabric placed above the under-drain acts as an impediment to direct gravitational flow and causes the water to move laterally and then down toward the under-drain (personal communication, Derek Winogradoff, August 2004).

Surface overflow

Surface overflow can be provided by surface drains installed at the designed maximum ponding elevations that are connected to under-drain systems, or by overflow channels connected to downstream surface conveyance, such as bioretention swales and open space areas. Safe discharge points are necessary to convey flows that exceed the capacity of the facility and to protect adjacent natural site features and property.

Hydraulic restriction layers

Adjacent roads, foundations or other infrastructure may require that infiltration pathways are restricted to prevent excessive hydrologic loading. Three types of restricting layers can be incorporated into bioretention designs:

- Filter fabric can be placed along vertical walls to reduce lateral flows.
- Clay (bentonite) liners are low permeability liners. Where clay liners are used under-drain systems are necessary. See 2005 SMMWW Volume IV section 4.4.3 for guidelines.
- Geomembrane liners completely block flow and are used for groundwater protection when bioretention facilities are used for filtering stormflows from pollutant hotspots. Where geomembrane liners are used under-drain systems are necessary. The liner should have a minimum thickness of 30 mils and be ultraviolet (UV) resistant.

Plant materials

Plant roots aid in the physical and chemical bonding of soil particles that is necessary to form stable aggregates, improve soil structure, and increase infiltration capacity. During the wet months in the Pacific Northwest (November through March) interception and evaporation are the predominant above-ground mechanisms for attenuating precipitation in the native forest setting. Transpiration during the non-growing wet months is minimal (see Introduction for details). In a typical bioretention cell, transpiration is negligible unless the cell has a dense planting of trees, the stand is relatively mature (10 to 20 years), and the canopy structure is closing and varied. The relatively mature and dense canopy structure is necessary for adequate interception and advective evaporation in winter months. The primary and significant

benefits of small trees, shrubs, and ground cover in bioretention areas during the wet season are the presence of root activity and contribution of organic matter that aids in the development of soil structure and infiltration capacity. See Appendix 3 for a bioretention plant table describing plant characteristics and optimum location within the bioretention area.

The primary design considerations for plant selection include:

- *Soil moisture conditions:* Plants should be tolerant of summer drought, ponding fluctuations, and saturated soil conditions for the lengths of time anticipated by the facility design.
- *Expected pollutant loadings:* Plants should tolerate typical pollutants and loadings from the surrounding land uses.
- *Above and below ground infrastructure in and near the facility:* Plant size and wind firmness should be considered within the context of the surrounding infrastructure. Rooting depths should be selected to not damage underground utilities if present. Slotted or perforated pipe should be more than 5 feet from tree locations (if space allows).
- *Adjacent plant communities and potential invasive species control.*
- *Site distances and setbacks for roadway applications.*
- *Visual buffering:* Plants can be used to buffer structures from roads, enhance privacy among residences, and provide an aesthetic amenity for the site.
- *Aesthetics:* Visually pleasing plant designs add value to the property and encourage community and homeowner acceptance. Homeowner education and participation in plant selection and design for residential projects should be encouraged to promote greater involvement in long-term care.

In general, the predominant plant material utilized in bioretention areas are facultative species adapted to stresses associated with wet and dry conditions (Prince George's County, 2002). Soil moisture conditions will vary within the facility from saturated (bottom of cell) to relatively dry (rim of cell). Accordingly, wetland plants may be used in the lower areas, if saturated soil conditions exist for appropriate periods, and drought-tolerant species planted on the perimeter of the facility or on mounded areas (Figure 6.1.14). See Appendix 3 for recommended plant species.

Planting schemes will vary with the surrounding landscape and design objectives. For example, plant themes can reflect surrounding wooded or prairie areas. Monoculture planting designs are not recommended. As a general guideline, a minimum of three tree, three shrubs, and three herbaceous groundcover species should be incorporated to protect against facility failure due to disease and insect infestations of a single species (Prince George's County, 2002). See Figure 6.1.15 for a sample planting plan.

Native plant species, placed appropriately, tolerate local climate and biological stresses and usually require no nutrient or pesticide application in properly designed soil mixes. Natives can be used as the exclusive material in a rain garden or in combination with hardy cultivars that are not invasive and do not require chemical inputs. In native landscapes, plants are often found in associations that grow together well given specific moisture, sun, soil, and plant chemical interactions. Native plant associations can, in part, help guide planting placement. For example, in partial sun and well-drained soils, beaked hazelnut (*Corylus cornuta*) and common snowberry (*Symphoricarpos albus*) are a common association in western Washington (Leigh, 1999). To increase survival rates and ensure quality of plant material, the following guidelines are suggested:

Figure 6.1.14 Examples of plants appropriate for different soil moisture zones in a bioretention area.

See Appendix 3 for a bioretention plant list organized by soil moisture zones.

Graphic by AHBL Engineering

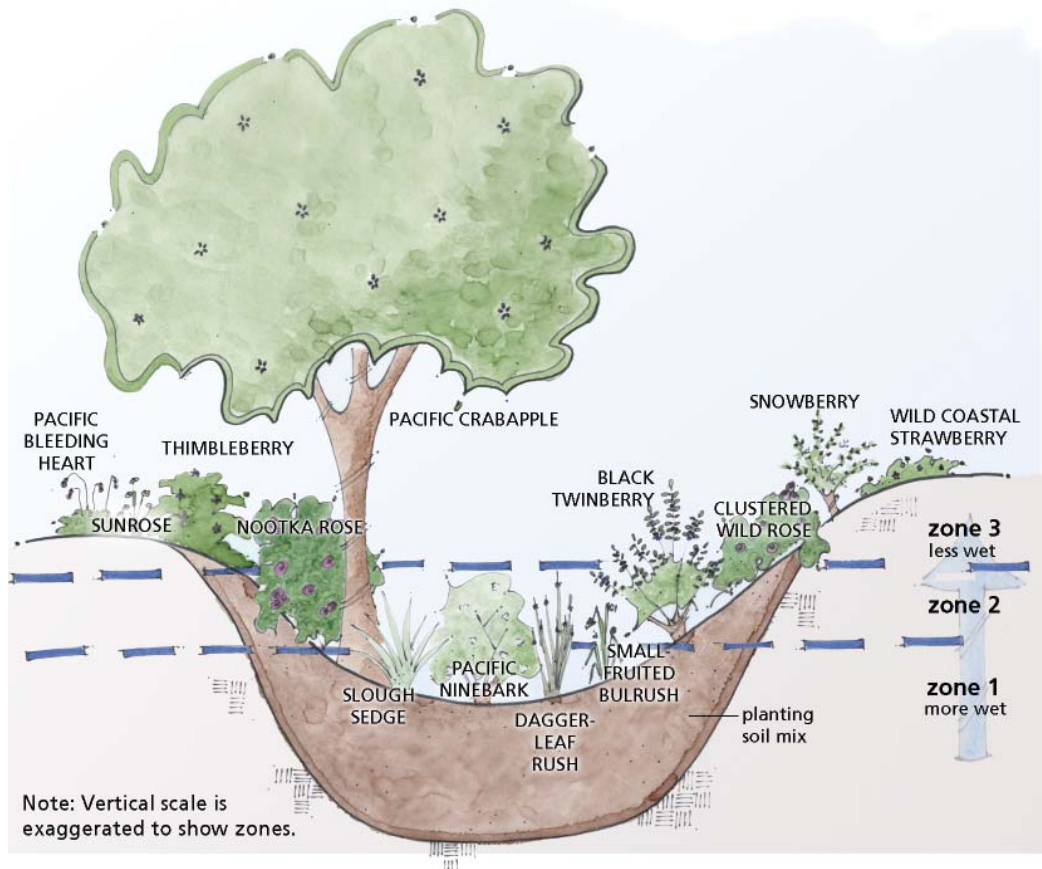
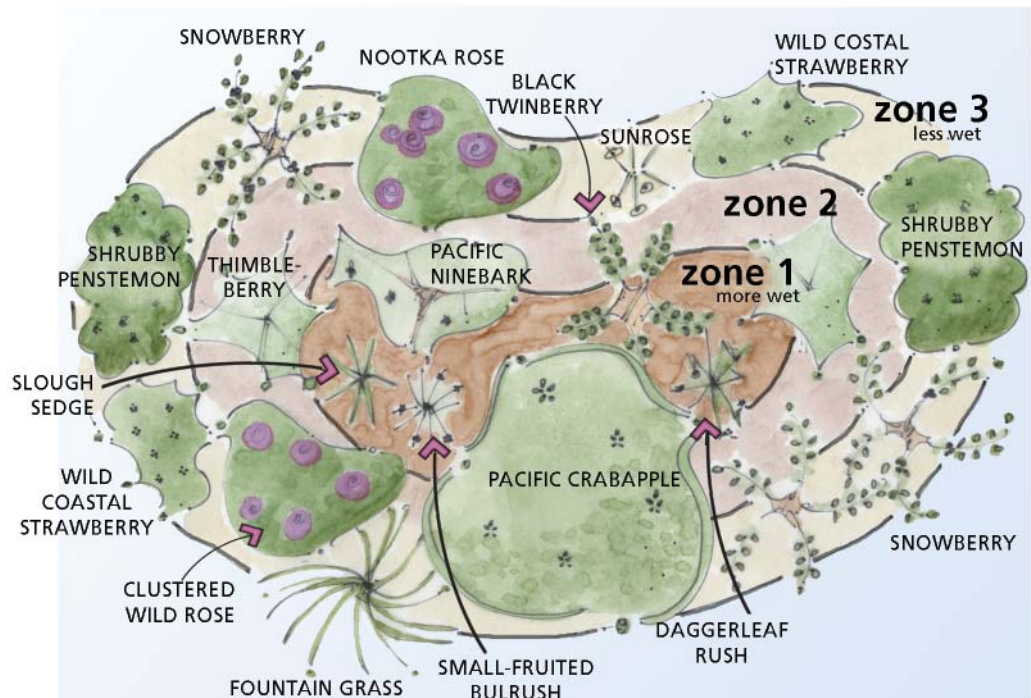


Figure 6.1.15 Sample planting plan for a bioretention area.

Graphic by AHBL Engineering



- Plants should conform to the standards of the current edition of *American Standard for Nursery Stock* as approved by the American Standards Institute, Inc. All plant grades shall be those established in the current edition of *American Standards for Nursery Stock* (current edition: ANSI Z60.1-2004) (Low Impact Development Center, 2004).
- All plant materials should have normal, well-developed branches and vigorous root systems, and be free from physical defects, plant diseases, and insect pests.
- Plant size: Bioretention areas provide excellent soil conditions and should have well defined maintenance agreements. In this type of environment small plant material provides several advantages and is recommended. Specifically, small plant material requires less careful handling, less initial irrigation, experiences less transplant shock, is less expensive, adapts more quickly to a site, and transplants more successfully than larger material (Sound Native Plants, 2000). Small trees and shrubs are generally supplied in pots of 3 gallons or less.
- All plants should be tagged for identification when delivered.
- Optimum planting time is fall (beginning early October). Winter planting is acceptable; however, extended freezing temperatures shortly after installation can increase plant mortality. Spring is also acceptable, but requires more summer watering than fall plantings. Summer planting is the least desirable and requires regular watering for the dry months immediately following installation.

Mulch layer

Bioretention areas can be designed with or without a mulch layer; however, there are advantages to providing a mulch application or a dense groundcover. Research indicates that most attenuation of heavy metals in bioretention cells occurs in the first 1 to 2 inches of the mulch layer. That layer can be easily removed or added to as part of a standard and periodic landscape maintenance procedure. No indications of special disposal needs are indicated at this time from older bioretention facilities in the eastern U.S. (personal communication, Larry Coffman). Properly selected mulch material also reduces weed establishment, regulates soil temperatures and moisture, and adds organic matter to soil. When used, mulch should be:

- Compost in the bottom of the facilities (compost is less likely to float and is a better source for organic materials) and shredded or chipped hardwood or softwood in surrounding areas.
- Free of weed seeds, soil, roots and other material that is not **bole** or branch wood and bark.
- A maximum of 2 to 3 inches thick (thicker applications can inhibit proper oxygen and carbon dioxide cycling between the soil and atmosphere) (Prince George's County, 2002).

Mulch should **not** be:

- Grass clippings (decomposing grass clippings are a source of nitrogen and are not recommended for mulch in bioretention areas).
- Pure bark (bark is essentially sterile and inhibits plant establishment).

Dense groundcover enhances soil structure from root activity, does not have the tendency to float during heavy rain events, inhibits weed establishment, provides additional aesthetic appeal, and is recommended when heavy metal loading is not anticipated (Prince George's County, 2002). Mulch is recommended in conjunction with the groundcover until groundcover is established.

Soil

Proper soil specification, preparation and installation are the most critical factors for bioretention performance. Soil specifications can vary according to the design objectives. Five different soil specifications are provided in Appendix 2 to illustrate various design approaches. In general, soil designed for bioretention areas should have the following characteristics:

- The texture for the soil component of the bioretention soil mix should be loamy sand (USDA Soil Textural Classification).
- The final soil mix (including compost and soil) should have a minimum long-term hydraulic conductivity of 1.0 inch/hour per ASTM Designation D 2434 (Standard Test Method for Permeability of Granular Soils) at 80 percent compaction per ASTM Designation D 1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort) (Tackett, 2004). Infiltration rate and hydraulic conductivity are assumed to be approximately the same in a uniform mix soil.
- The final soil mixture should have a minimum organic content of 10 percent by dry weight per ASTM Designation D 2974 (Standard Test Method for Moisture, Ash and Organic Matter of Peat and Other Organic Soils) (Tackett, 2004). Currently, gravelly sand bioretention soil mixtures for bioretention areas are being developed and installed to provide adequate infiltration rates at 85 to 95 percent compaction. While designers anticipate good performance from this specification, the mix may be slightly less than optimal for plant growth and has not been tested long-term for plant health performance (see Engineered Soil Mix and Bioretention Soil Mix 2 and 3 in Appendix 2).
- Achieving the above recommendations will depend on the specific soil and compost characteristics. In general, the recommendation can be achieved with 60 to 65 percent loamy sand mixed with 35 to 40 percent compost or 30 percent sandy loam, 30 percent coarse sand, and 40 percent compost.
- The final soil mixture should be tested by an independent laboratory prior to installation for fertility, micronutrient analysis, and organic material content. Soil amendments per laboratory recommendations (if any) should be uniformly incorporated for optimum plant establishment and early growth (Tackett, 2004).
- Clay content for the final soil mix should be less than 5 percent.
- The pH for the soil mix should be between 5.5 and 7.0 (Stenn, 2003). If the pH falls outside of the acceptable range, it may be modified with lime to increase the pH or iron sulfate plus sulfur to lower the pH. The lime or iron sulfate must be mixed uniformly into the soil prior to use in bioretention area (Low Impact Development Center, 2004).
- Soil depth should be a minimum of 18 inches to provide acceptable minimum pollutant attenuation and good growing conditions for selected plants. A minimum depth of 24 inches should be selected for improved phosphorus and nitrogen (TKN and ammonia) removal. Deeper soil profiles (> 24 inches) can enhance phosphorus, TKN and ammonia removal (Davis, Shokouhian, Sharma and Minami, 1998). Nitrate removal in bioretention cells can be poor and in some cases cells can generate nitrate due to nitrification (Kim et al., 2003). See under-drain section for design recommendations to enhance nitrate removal. Deeper or shallower profiles may be desirable for specific plant, soil, and storm flow management objectives.
- The soil mix should be uniform and free of stones, stumps, roots or other similar material > 2 inches.

Organic matter content of soil mixes

A quick way to determine the approximate organic matter content of a soil mix:

- Compost is typically 40-50% organic matter (use 50% as an average).
- Compost weighs approximately 50% as much as loam.
- A mix that is 40% compost measured by volume is roughly 20% organic matter by volume.
- Compost is only 50% as dense as the soil, so the mix is approximately 10% organic matter by weight (the organic matter content in soil is determined by weighing the organic material before combustion and then weighing the ash post-combustion).

- To reduce transportation and disposal needs, on-site excavated soil, rather than imported soil, can be used. However, using on-site excavated soil for the amended soil mix may reduce control over gradation, organic content, and final product performance, can increase project costs, and can complicate construction logistics when attempting to blend soil mix components in restricted space or during winter months (personal communication, Tracy Tackett). If on-site excavated soil is used, representative samples should be tested for gradation and adjusted, if necessary, to attain adequate infiltration capability.
- The above guidelines should provide a soil texture, organic content, and infiltration rate suitable to meet Ecology's SSC-6 "Soil Physical and Chemical Suitability for Treatment" recommendations for designing infiltration systems. A soils report evaluating these parameters should be provided to verify the treatment capability of the soil mix.

Compost

See Section 6.2.2 for compost specifications.

6.1.2.4 Installation

Excavation

Soil compaction can lead to facility failure; accordingly, minimizing compaction of the base and sidewalls of the bioretention area is critical (Prince George's County, 2002). Excavation should not be allowed during wet or saturated conditions. Excavation should be performed by machinery operating adjacent to the bioretention facility and no heavy equipment with narrow tracks, narrow tires, or large lugged, high pressure tires should be allowed on the bottom of the bioretention facility (Tackett, 2004). If machinery must operate in the bioretention cell for excavation, use light weight, low ground-contact pressure equipment and rip the base at completion to refracture soil to a minimum of 12 inches (Prince George's County, 2002).

Sidewalls of the facility, to the height of the grade established by the designed soil mix, can be vertical if soil stability is adequate. Exposed sidewalls should be no steeper than 3H:1V. The sidewalls and bottom should be roughened where scraped and sealed by excavation equipment (Prince George's County, 2002). The bottom of the facility should be flat.

Vegetation protection areas with intact native soil and vegetation should not be cleared and excavated for bioretention facilities.

Soil installation

On-site soil mixing or placement should not be performed if soil is saturated. The bioretention soil mixture should be placed and graded by excavators and/or backhoes operating adjacent to the bioretention facility. If machinery must operate in the bioretention cell for soil placement or soil grading, use light weight, low ground-contact pressure equipment. The soil mixture should be placed in horizontal layers not to exceed 12 inches per lift for the entire area of the bioretention facility.

The soil mixture will settle and proper compaction can be achieved by allowing time for natural compaction and settlement. To speed settling, each lift can be watered until just saturated. Water for saturation should be applied by spraying or sprinkling.

An appropriate sediment control device should be used to treat any sediment-laden water discharged from an under-drain (Low Impact Development Center, 2004).

Sediment Control

Erosion and sediment problems are most difficult during clearing, grading, and construction; accordingly, minimizing site disturbance to the greatest extent practicable is the most effective sediment control. Bioretention facilities should not be used as sediment control facilities and all drainage should be directed away from bioretention facilities after initial rough grading. Flow can be directed away from the facility with temporary diversion swales or other approved protection (Prince George's County, 2002). Bioretention facilities should not be constructed until all contributing drainage areas are stabilized according to erosion and sediment control BMPs and to the satisfaction of the engineer. Erosion and sediment control practices must be inspected and maintained on a regular basis. If deposition of fines occurs in the bioretention area, material should be removed and the surface scarified to the satisfaction of the project engineer (Prince George's County, 2002).

6.1.3 Maintenance

Bioretention areas require annual plant, soil, and mulch layer maintenance to ensure optimum infiltration, storage, and pollutant removal capabilities. In general, bioretention maintenance requirements are typical landscape care procedures and include:

- *Watering:* Plants should be selected to be drought tolerant and not require watering after establishment (2 to 3 years). Watering may be required during prolonged dry periods after plants are established.
- *Erosion control:* Inspect flow entrances, ponding area, and surface overflow areas periodically, and replace soil, plant material, and/or mulch layer in areas if erosion has occurred. Properly designed facilities with appropriate flow velocities should not have erosion problems except perhaps in extreme events. If erosion problems occur the following should be reassessed: (1) flow volumes from contributing areas and bioretention cell sizing; (2) flow velocities and gradients within the cell; and (3) flow dissipation and erosion protection strategies in the pretreatment area and flow entrance. If sediment is deposited in the bioretention area, immediately determine the source within the contributing area, stabilize, and remove excess surface deposits.
- *Plant material:* Depending on aesthetic requirements, occasional pruning and removing dead plant material may be necessary. Replace all dead plants and if specific plants have a high mortality rate, assess the cause and replace with appropriate species. Periodic weeding is necessary until plants are established. The weeding schedule should become less frequent if the appropriate plant species and planting density have been used and, as a result, undesirable plants excluded.
- *Nutrient and pesticides:* The soil mix and plants are selected for optimum fertility, plant establishment, and growth. Nutrient and pesticide inputs should not be required and may degrade the pollutant processing capability of the bioretention area, as well as contribute pollutant loads to receiving waters. By design, bioretention facilities are located in areas where phosphorous and nitrogen levels are often elevated and these should not be limiting nutrients. If in question, have soil analyzed for fertility.

- *Mulch*: Replace mulch annually in bioretention facilities where heavy metal deposition is likely (e.g., contributing areas that include parking lots and roads). In residential lots or other areas where metal deposition is not a concern, replace or add mulch as needed to maintain a 2 to 3 inch depth at least once every two years.
- *Soil*: Soil mixes for bioretention facilities are designed to maintain long-term fertility and pollutant processing capability. Estimates from metal attenuation research suggest that metal accumulation should not present an environmental concern for at least 20 years in bioretention systems (see Performance section below). Replacing mulch in bioretention facilities where heavy metal deposition is likely provides an additional level of protection for prolonged performance. If in question, have soil analyzed for fertility and pollutant levels.

6.1.4 Performance

Pollutant removal processes in bioretention

All primary pathways for removing pollutants from storm flows are active in bioretention systems. Schueler and Clayton (1996) list the following as the primary pathways:

- *Sedimentation* is the settling of particulates (not effective for removing soluble components). Sedimentation occurs in the pretreatment (if provided) and ponding area of the facility.
- *Filtration* is the physical straining of particulates (not an effective mechanism for removing soluble components). Some filtration occurs in the ponding area as stormwater moves through plants, but the soil is the primary filtering media. Pitt et al., (1995) report that 90 percent of small particles commonly found in urban storm flows (6 to 41 microns) can be trapped by an 18-inch layer of sand. This level of performance can be anticipated for bioretention soils typically high in sand content.
- *Adsorption* is the binding of ions and molecules to electrostatic receptor sites on the filter media particles. This is the primary mechanism for removing soluble nutrients, metals, and organics that occur in the soil of bioretention areas as storm flows infiltrate. Adsorption increases with increased organic matter, clay, and a neutral to slightly alkaline pH.
- *Infiltration* is the downward movement of surface water to interstitial soil water. This process initiates adsorption, microbial action, etc., for pollutant removal.
- *Phytoremediation* processes include degradation, extraction by the plant, containment within the plant (assimilation) or a combination of these mechanisms (USEPA, 2000). Studies have shown that vegetated soils are capable of more effective degradation, removal, and mineralization of total petroleum hydrocarbons (TPHs), polycyclic aromatic hydrocarbons (PAHs), pesticides, chlorinated solvents, and surfactants than are non-vegetated soils (USEPA, 2000). Certain plant roots can absorb or immobilize metal pollutants, including cadmium, copper, nickel, zinc, lead, and chromium, while other species are capable of metabolizing or accumulating organic and nutrient contaminants. A University of Maryland study found significant metal accumulation in creeping juniper plants in pilot-scale bioretention cells. Copper increased by a factor of 6.3, lead by a factor of 77, and zinc by a factor of 8.1 in the tissue of junipers after receiving synthetic stormwater applications compared to pre-application tissue samples (Davis, Shokouhian, Sharma,

Minami and Winogradoff, 2003). An intricate and complex set of relationships and interactions between plants, microbes, soils, and contaminants make these various phytoremediation processes possible (see Appendix 5 for a more detailed discussion of phytoremediation and stormwater).

- *Plant resistance* occurs as plant materials reduce flow velocities and increase other pollutant removal pathways such as sedimentation, filtering, and plant uptake of pollutants during growth periods.
- *Volatilization* occurs when a substance is converted to a more volatile vapor form. Transforming complex hydrocarbons to carbon dioxide is an example of volatilization active in bioretention cells (Prince George's County, 2002).
- *Thermal attenuation* reduces water temperatures as storm flows move through subsurface soil layers. A field study in Maryland found that the temperature of the input water was reduced by approximately 12 degrees C after infiltrating through a bioretention cell located in a parking lot (USEPA, 2000a).

Pollutant removal efficiency in bioretention areas

Metals

Laboratory and field research indicates that bioretention areas have excellent removal capabilities for heavy metals. Duration and flow rate can influence removal at shallow depths (10 inches), but not deeper in the soil profile (36 inches). Metal adsorption in soil is typically influenced by pH; however, the buffering capacity in the bioretention soil mix effectively negates the influence of pH variations in synthetic pollutant mixtures applied to pilot-scale systems (Davis et al., 2003). The most significant metal uptake occurs in the mulch layer that can retain a large portion of the total metals loads (Davis et al., 2001).

Table 6.1.1 summarizes percentages of pollutants removed from pilot-scale laboratory studies performed at University of Maryland. Also see Appendix 4 for summaries of bioretention swale and bioretention cell research. Table 6.1.2 provides data summarizing research on other typical stormwater BMPs for comparison.

Table 6.1.1 Percent pollutant removal by depth in bioretention facilities.

Depth (inches)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)	P (mg/L)	TKN (mg/L)	NH4 (mg/L)	NO3 (mg/L)	TN (mg/L)
10	90	93	87	0	37	54	-97	-29
22	93	>97	>96	73	60	86	-194	0
36	93	>97	>96	81	68	79	23	43

Adapted from Davis et al., 1998 (removal percentages are for total metals)

Table 6.1.2 Comparative pollutant removal capability of stormwater treatment practices (in percentages).

Pollutant	Dry Extended Detention Pond	Wetlands	Water Quality Swales	Ditches
TN (mg/L)	31	30	84	-9
NO ₃ (mg/L)	ND	ND	ND	ND
P (mg/L)	20	49	34	-16
Cu (µg/L)	26	40	51	14
Pb (µg/L)	54	68	67	17
Zn (µg/L)	26	44	71	0

Adapted from CWP, 2000b (removal percentages are for total metals)

Nutrients

Phosphorus removal in bioretention soils increases with depth of facility. Sorption of phosphorus onto aluminum, iron, and clay minerals in the soil is the likely mechanism of removal (Davis et al., 2001). Phosphorus can **desorb** if low pH or low oxygen conditions are present; accordingly, bioretention planting soil dewatering rate and drying should be maintained and pH monitored annually. Nitrate removal is highly variable, but generally poor and at times nitrate production and export has been observed (Kim et al., 2003). Production or export of nitrate is a result of organic and ammonia nitrogen that is converted to nitrate between storms (presumably through the **ammonification** and **nitrification** process). Nitrate is then washed from the facility during subsequent storm events (Kim et al., 2003).

Where nitrate is a concern, an under-drain can be elevated from the bottom of the bioretention facility and within the gravel blanket to create a fluctuating anaerobic/aerobic zone below the drain pipe. With a suitable carbon source (e.g., wood chips mixed in the gravel) acting as an electron donor, the anaerobic zone can enhance the denitrification process (see Figure 6.1.13 in the Under-drain section) (Kim et al., 2003).

Hydrocarbons and bacteria

Hong, Seagren and Davis (2002) examined the capacity of a mulch layer to capture oil and grease via sorption and filtration. Simulated stormwater runoff carrying naphthalene was applied to a bench-scale “reactor” with a 3-cm thick leaf compost layer. During the simulated storm event approximately 90 percent of dissolved naphthalene was removed from aqueous phase via sorption. After the simulated storm event (37 and 40 hours) approximately 32 percent of the naphthalene was removed from the solid phase via biodegradation in the mulch layer where the microbial population had been inhibited. Approximately 72 percent of the naphthalene was removed from the solid phase via biodegradation in the mulch layer at 37 and 40 hours and 95 percent after 74 hours where the microbial population was not inhibited. Losses due to volatilization were negligible. See bioretention research in Appendix 4 for more detail. No research for bacteria removal in bioretention areas has currently been located.

Stormwater pollutants can disrupt normal soil function by lowering cation exchange capacity. The oldest bioretention facilities operating in the U.S. (approximately 10 years) appear to develop soil structure and maintain soil functions that actually enhance pollutant processing capability (Prince George’s County, 2002). Estimates from research suggest that metal accumulation would not present an environmental concern for at least 20 years in bioretention systems (Davis et al., 2003).

Flow control processes in bioretention

- *Evaporation* can occur as precipitation is intercepted by vegetation, from surface water in the ponding area, and from exposed soil or mulch layers in bioretention areas. Evaporation from vegetation is relatively minor unless the cell has a well developed, closed, and varied canopy.
- *Infiltration* is the downward migration of runoff through the planting soil and into the surrounding soils. Infiltration is the primary mechanism for attenuating storm flows in bioretention areas. In general, long-term infiltration rates degrade over time in typical infiltration facilities due to large hydrologic loads, biofilm, and sedimentation. Anecdotal information suggests that properly designed bioretention area soil infiltration rates do not degrade as rapidly and may improve over time due to biological, chemical, and physical processes that build soil structure. Focused studies have not confirmed this. The surrounding soil will be the limiting infiltration rate in till, compacted silt or clay or other tight soils; however, there are no studies quantifying vertical and lateral subsurface flows from bioretention areas in the Puget Sound region.

Flow control performance

In the city of Seattle, Seattle Public Utilities narrowed 660 feet of conventional residential road and installed bioretention swales within the right-of-way as part of the Street Edge Alternatives (SEA) Street project. A v-notch weir installed at the ultimate outfall of the project measured surface flow volumes and timing. The contributing area with swales is approximately 2.3 acres. Soils underlying the bioretention swales are heterogeneous till-like material with lens of silt, sand, and gravel of varying permeability. Some of the swales are lined with bentonite to restrict infiltration and reduce concerns of wet basements in homes near the swales. Flows for the conventional pre-construction street were compared to the retrofit design. During the pre-construction period (March-July 2000), 7.96 inches of rainfall produced 4979 cubic feet of runoff. During the post-construction period (March-July 2001), 9.00 inches of precipitation produced 132 cubic feet of runoff. Post-construction runoff volumes were reduced by approximately 97 percent compared to pre-construction volumes. An October 2003 record storm event (4.22 inches with a 32.5 hour storm duration) produced no runoff (Horner et al., 2002).

6.1.5 Costs

The city of Seattle is implementing a new Natural Drainage System Program (NDS) for retrofitting residential streets that replaces conventional curb and gutter or roadside ditches with bioretention swales. Two designs are used depending on the gradient. The SEA Street swales are designed for the lower gradient north-south streets, and the Cascade type (which incorporate catch basins or check dams between longer gravel bottom swales) are used on the higher gradient east-west streets. Both types use compost-amended soil and small trees, shrubs, and groundcover within the swale to provide enhanced storage, infiltration, and pollutant removal. (See Figure 6.1.16 for SEA Street design example.) Table 6.1.3 compares the estimated costs of a traditional curb and gutter street retrofit to a bioretention swale design with no curb and gutter and enhanced landscaping. Costs shown include comparable water quality treatment and detention volume.

Table 6.1.3 Cost comparisons for the NDS and conventional drainage designs

Street Type	Local Street SEA Street	Local Street conventional	Collector Street Cascade	Collector Street Conventional	Broadview Green Grid
Transportation & aesthetics	<ul style="list-style-type: none"> • 1 sidewalk per block • New street paving • Traffic calming • Enhanced landscaping 	<ul style="list-style-type: none"> • 2 sidewalks per block • New street paving • No traffic calming • Conventional landscaping 	<ul style="list-style-type: none"> • No street improvement • Enhanced landscaping 	<ul style="list-style-type: none"> • No street improvement • Conventional landscaping 	<ul style="list-style-type: none"> • Incorporates SEA Street and Cascade type designs • 1 sidewalk per block • New paving • Enhanced landscaping
Stormwater management	<ul style="list-style-type: none"> • Higher protection for aquatic biota • More closely mimics natural hydrology • Bio-remediate pollutants 	<ul style="list-style-type: none"> • Flood protection focus • Water quality treatment 	<ul style="list-style-type: none"> • Improved water quality treatment • Some flood protection 	<ul style="list-style-type: none"> • Flood protection focus • Water quality treatment 	<ul style="list-style-type: none"> • Higher water quality and aquatic biota protection • Some flood protection
% impervious area	35%	35%	35%	35%	35%
Cost per block (330 linear ft)	\$325,000	\$425,000	\$285,000	\$520,400	Average/block \$280,000

Adapted from *Cost Analysis of Natural vs. Traditional Drainage Systems Meeting NDS Stormwater Goals*, 2004



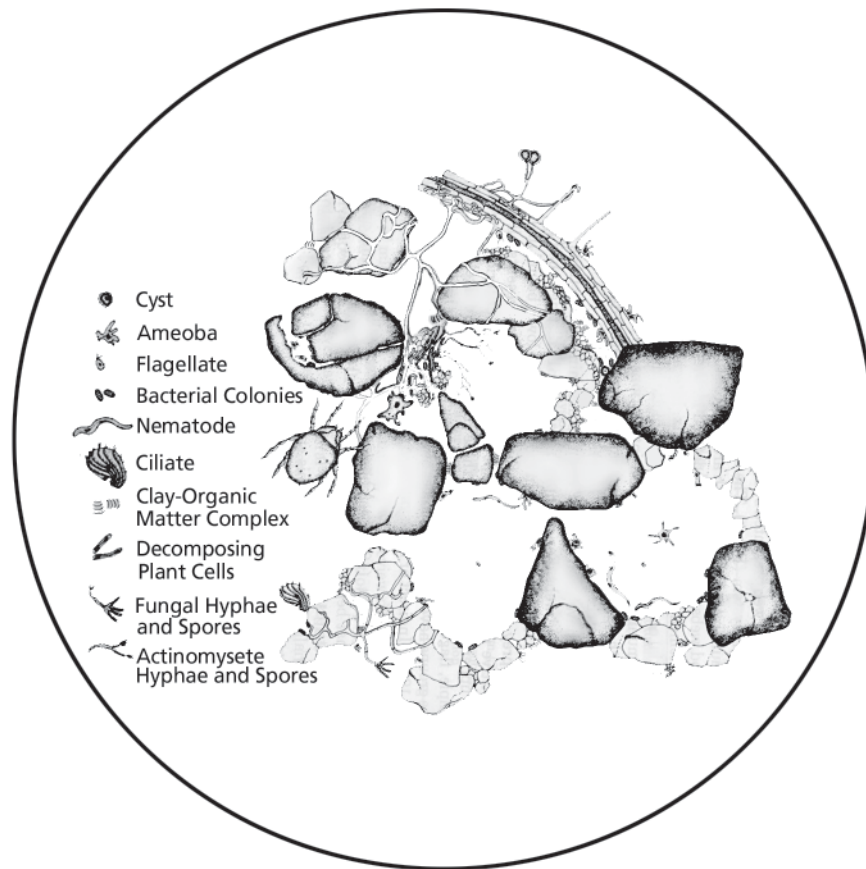
Figure 6.1.16 SEA Street bioretention swale, Seattle.
Photo by Colleen Owen

6.2 Amending Construction Site Soils

Native soils are highly complex systems that provide essential environmental benefits including biofiltration of pollutants, nutrients for plant growth, and the storage and slow release of storm flows. The ability of soil to effectively store and slowly release water is dependent on soil texture, structure, depth, organic matter content, and biota (Washington Organic Recycling Council [WORC], 2003). Plant roots, macro fauna, and microbes tunnel, excavate, penetrate and physically and chemically bond soil particles to form stable aggregates that enhance soil structure and porosity. Micro-and macro-pores provide a balance of environments that improve water-holding capability, increase infiltration capacity, increase oxygen levels, and provide a variety of habitats necessary to support thousands of different organisms within the soil (Allen, 1994 and CH2M HILL, 2000).

Organic matter is a critical component of a functioning soil system. Mixed into the soil, organic matter absorbs water, physically separates clay and silt particles, and reduces erosion (Balousek, 2003 and WORC, 2003). Microbial populations and vegetation depend on the replenishment of organic matter to retain and slowly release nutrients for growth (Chollak, n.d.). Typically, native Puget Sound forest soils have an organic matter content of 4 to 6 percent and the sub-soils less than 1 percent (Chollak, n.d.). Construction activity removes the upper layers of soil, compacts exposed sub-soils low in organic matter, and alters the site's hydrologic characteristics by converting the predominantly subsurface flow regime of the pre-disturbance site to primarily overland flow.

Figure 6.2.1 Close up of healthy soil structure.
Graphic courtesy of S. Rose and E.T. Elliott



Current landscape practices often do not encourage adequate preparation of turf and planting bed areas in order to regain any of the hydrologic benefits of native soils. As a result, compacted, unamended soil in landscape areas can behave similarly to impervious surfaces by generating considerable overland or shallow subsurface flows that rapidly reach receiving waters. A three-year study of a 17-hectare developed catchment near Seattle (approximately 71 percent coverage in lawn, gardens, and common areas) found that 60 percent of the total overland and rapid subsurface flow came from landscaped areas during large storms (Wigmosta, Burges and Meena, 1994). Without proper treatment and maintenance, compacted soil in lawn areas can take several years to decades to recover any beneficial infiltration and water storage characteristics of the pre-development condition (Leg, Bannerman and Panuska, 1996).

Compacted, unamended soil in landscaped areas can have similar characteristics of impervious surfaces and generate considerable overland or shallow subsurface flows that rapidly reach receiving waters.

The following section focuses on soil amendment guidelines for general landscape and vegetation protection areas. For specific application of soils in bioretention facilities see Section 6.1: Bioretention Areas.

6.2.1 Applications

The hydrologic characteristics of disturbed construction site soils for commercial, residential, and industrial projects, whether new or retrofit, can be enhanced with the addition of organic matter (CH2M HILL, 2000). In a low impact development, the landscape component of the project enhances water storage, attenuates storm flows, and is integral to the stormwater management design. When properly implemented and maintained, incorporating compost into the disturbed soils provides hydrologic, as well as other important environmental, functions including:

In a low impact development, the landscape component of the project enhances water storage, attenuates storm flows, and is integral to the stormwater management design.

- Reduced erosion.
- Increased sediment filtration.
- Pollutant adsorption and biofiltration.
- Improved plant growth, disease resistance, and overall aesthetics of the landscaping.
- Reduced (or elimination of) pesticide and fertilizer inputs for plant maintenance.
- Reduced peak summer irrigation needs (Chollak, n.d.).

Organic matter derived from compost, stockpiled on-site soil, or imported topsoil can be beneficial in all areas subject to clearing and grading. Engineered structural fill or LID drainage facilities will have specific design requirements for soil (see Section 6.1 for soil specifications in bioretention facilities). Application rates and techniques for incorporating amendments will vary with the use and plant requirements of the area. For example, application depths will be less in tree root protection zones than in turf and planting beds, and turf requiring maintenance or supporting foot traffic during the wet months will require different application rates than general landscaping areas (see Section 6.2.2: Design for details).

6.2.2 Design

Much of the information supplied here is a summary of *Guidelines and Resources for Implementing Soil Depth and Quality BMP T.5.13 in WDOE Western Washington Stormwater Manual* (Stenn, 2003). An update of this guidance is available at: <http://www.soilsforsalmon.org>. For details on specifications, verification, and inspection procedures, and additional resources consult the above cited manual.

To enhance the hydrologic and other environmental benefits of disturbed soils in a low impact development, the topsoil should have the following characteristics:

- A minimum organic matter content of 10 percent by dry weight for all planting beds and other landscaped areas (except turf requiring access during wet months).
- Organic matter content in turf areas that requires maintenance or supports foot traffic during the wet months should be 5 percent by dry weight.
- pH between 5.5 and 7.0 or a pH appropriate for installed plants.
- A minimum depth of 8 inches (except in tree root protection areas—see next page).
- Planting beds should be mulched with 2 to 3 inches (maximum) of organic material.
- Subsoils below topsoil applications should be scarified to a depth of at least 4 inches and some topsoil material incorporated to prevent stratification. See tilling recommendations below for specific application methods.

The minimum organic matter content may be achieved by using the pre-approved amendment methods as outlined below, or by calculating a custom amendment rate for the existing site soil conditions. The pre-approved method simplifies planning and implementation; however, the organic matter content of the disturbed on-site soils may be relatively good and not require as extensive an application of amendment material. In many cases, calculating a site-specific rate may result in significant savings in amendment material and application costs. Calculating a custom rate requires collecting soil samples from the area to be amended and samples from the compost material. The soil is then tested for bulk density and percent organic matter. The compost is tested for bulk density, percent organic matter, moisture content, carbon-to-nitrogen ratio, and heavy metals. Compost and topsoil producers can often supply the required information for the amendment material; however, on-site analysis would be necessary if vendor-supplied analysis is not available. See *Guidelines and Resources for Implementing Soil Depth and Quality BMP T.5.13 in WDOE Western Washington Stormwater Manual* (Stenn, 2003) for additional information on testing procedures.

Determining the site-specific compost application rate is calculated with the following equation:

$$CR = D (X) \frac{SBD (SOM\% - FOM\%)}{SBD (SOM\% - FOM\%) - CBD (COM\% - FOM\%)}$$

Where:

CR = compost application rate (inches)

D = depth of incorporation (inches)

SBD = soil bulk density (lb/cubic yard dry weight)

SOM% = initial soil organic matter (%)

FOM% = final target soil organic matter (%) (target will be 5% or 10% depending on landscape area)

CBD = compost bulk density (lb/cubic yard dry weight)

COM% = compost organic matter (%)

Recommended soil characteristics can be achieved by the following methods: (1) Set aside and protect native soil and vegetation areas; (2) Amend existing disturbed topsoil or subsoil; (3) Stockpile on-site topsoil from cleared and graded areas and replace prior to planting; or (4) Import topsoil with required organic matter content standards.

1. **Set aside and protect native soil and vegetation areas.**

The most effective and cost efficient method for providing the hydrologic benefits of healthy soil is to designate and protect native soil and vegetation areas. See Chapter 4: Vegetation Protection, Reforestation and Maintenance and Chapter 5: Clearing and Grading for conservation techniques.

The most effective and cost efficient method for providing the hydrologic benefits of healthy soil is to designate and protect native soil and vegetation areas.

2. **Amend existing disturbed topsoil or subsoil.**

Scarify or till soil to an 8-inch depth (or to depth needed to achieve a total depth of 12 inches of uncompacted soil after the calculated amount of amendment is added). The entire surface should be disturbed by scarification and amendment applied on soil surface. Do not scarify soil within the drip-line of existing trees to be retained. Within 3 feet of the tree drip-line, amendment should be incorporated no deeper than 3 to 4 inches to reduce damage to roots.

Landscaped Areas (10 percent organic content): Place and till 3 inches (or custom calculated amount) of composted material into 5 inches of soil (a total depth of about 9.5 inches, for a settled depth of 8 inches). Rake beds smooth, remove rocks larger than 2 inches diameter and mulch areas with 2 inches of organic mulch.

Turf Areas (5 percent organic content): Place and till 1.75 inches (or custom calculated amount) of composted material into 6.25 inches of soil (a total amended depth of about 9.5 inches, for a settled depth of 8 inches). Water or roll to compact soil to 85 percent of maximum. Rake to level, and remove surface woody debris and rocks larger than 1-inch diameter.

3. **Stockpile on-site topsoil from cleared and graded areas and replace prior to planting.**

Stockpile and cover soil with weed barrier or other breathable material that sheds moisture yet allows air transmission, in approved location, prior to grading. Test the stockpiled material and amend with organic matter or topsoil if required to achieve organic content to 8-inch depth. Replace stockpiled topsoil prior to planting.

If replaced topsoil plus compost or other organic material will amount to less than 12 inches, scarify or till subgrade to a depth needed to achieve 12 inches of loosened soil after topsoil and amendment are placed. The entire surface should be disturbed by scarification and amendment applied on soil surface. Do not scarify soil within drip-line of existing trees to be retained. Within 3 feet of tree drip-line, amendment should be incorporated no deeper than 3 to 4 inches to reduce damage to roots.

Landscaped Areas (10 percent organic content): Place and till 3 inches of composted material into 5 inches of replaced soil (a total depth of about 9.5 inches, for a settled depth of 8 inches). Rake beds to smooth, remove rocks larger than 2 inches diameter, and mulch areas with 2 inches of organic mulch or stockpiled duff.

Turf Areas (5 percent organic content): Place and till 1.75 inches of composted material into 6.25 inches of replaced soil (a total amended depth of about 9.5 inches, for a settled depth of 8 inches). Water or roll compact soil to 85 percent of maximum. Rake to level, and remove surface woody debris and rocks larger than 1-inch diameter.

4. **Import topsoil with required organic matter content standards.**

Scarify or till subgrade in two directions to a 6-inch depth. The entire surface should be disturbed by scarification and amendment applied on soil surface. Do not scarify soil within drip-line of existing trees to be retained. Within 3 feet of tree drip-line, amendment should be incorporated no deeper than 3 to 4 inches to reduce damage to roots.

Landscaped Areas (10 percent organic content): Use imported topsoil mix containing 10 percent organic matter (typically around 40 percent compost). The soil portion must be sand or sandy loam as defined by the USDA soil classification system. Place 3 inches of imported topsoil mix on surface and till into 2 inches of soil. Place 3 inches of topsoil mix on the surface. Rake smooth, remove surface rocks over 2 inches in diameter, and mulch planting beds with 2 inches of organic mulch.

Turf Areas (5 percent organic content): Use imported topsoil mix containing 5 percent organic matter (typically around 25 percent compost). Soil portion must be sand or sandy loam as defined by the USDA soil classification system. Place 3 inches of topsoil mix on surface. Water or roll to compact soil to 85 percent maximum. Rake to level and remove surface rocks larger than 1-inch diameter.

The soil portion of the topsoil must be sand or sandy loam as defined by the USDA soil classification system. The soil and compost mix should have less than 25 percent pass through a #200 sieve and 100 percent should pass through a 3/4-inch screen (WORC, 2003).

Compost

Organic soil amendment, suitable for landscaping and stormwater management, should be a stable, **mature compost** derived from organic waste materials including yard debris, manures, bio-solids, wood wastes or other organic materials that meet the intent of the organic soil amendment specification. **Compost stability** indicates the level of microbial activity in the compost and is measured by the amount of CO₂ produced over a given period of time by a sample in a closed container. Unstable compost can render nutrients temporarily unavailable and create objectionable odors.

Compost quality can be determined by examining the material and qualitative tests. A simple way to judge compost quality is to smell and examine the finished product, which should have the following characteristics (WORC, 2003):

- Earthy smell that is not sour, sweet or ammonia like.
- Brown to black in color.
- Mixed particle sizes.
- Stable temperature and does not get hot when re-wetted.
- Crumbly texture.

Qualitative tests and producer documentation should have the following specifications:

- Material must meet the definition for “composted materials” in WAC 173-350 section 220. This code is available online at <http://www.ecy.wa.gov/programs/swfa/facilities/350.html>.
- Organic matter content between 35 and 65 percent as determined by loss of ignition test method (ASTM D 2974).
- pH between 5.5 and 7.0.
- Carbon:nitrogen ratio between 20:1 and 35:1 (a CN ratio of 35:1 is preferred for native plantings).
- Maximum electrical conductivity of 3 ohms/cm.
- Moisture content range between 35 and 50 percent.
- No viable weed seeds.
- Manufactured inert material (plastic, concrete, ceramics, etc.) should be less than 1 percent on a dry weight or volume basis.
- Metals should not be in excess of limits in the following table:

Metal	Limit (mg/kg dry weight)
Arsenic	≤ 20 ppm
Cadmium	≤ 10 ppm
Copper	≤ 750 ppm
Lead	≤ 150 ppm
Mercury	≤ 8 ppm
Molybdenum	≤ 9 ppm
Nickel	≤ 210 ppm
Selenium I	≤ 18 ppm

(Stenn, 2003)

Determining final grade with amended soils

To achieve the appropriate grade, changes in soil depth from tilling and incorporating soil amendments need to be estimated.

The difference in volume of the dense versus the loose soil condition is determined by the “fluff factor” of the soil. The fluff factor of compacted subsoils in the Puget Sound area tends to be between 1.3 and 1.4. Tilling typically penetrates the upper 6 to 8 inches of the existing soil. Assuming a 6-inch depth is achieved, the depth adjusted by the fluff factor will correspond to a 7.8 to 8.4-inch depth of loose soil. This loose volume is then amended at a 2:1 ratio of loose soil to compost, corresponding to an imported amendment depth of approximately 4 inches for this example. In the loose state, both the soil and compost have a high percentage of pore space (volume of total soil not occupied by solids), and the final amended soil elevation must account for compost settling into void spaces of the loose soil and compaction (this example assumes that 15 percent of the soil’s void spaces become occupied by compost particles). For a fluff factor of 1.3, use a compression factor of 1.15 and for soils with a fluff factor of 1.4 use a compression factor of 1.2 (i.e., 15 to 20 percent of the soils’ void spaces will become occupied by compost particles). The resulting increase in elevation for soils amended to a 6-inch depth will be approximately 3 inches. See Table 6.2.1 for an example calculation.

Table 6.2.1 Example for estimating soil depth and height changes.

Procedure	Calculation	Relative Elevation Inches
Beginning Elevation		0
Rototill soil to a depth of 6 inches and assuming 1.4-inch fluff factor	Depth achieved by machinery x fluff factor of soil: $(6 \times 1.4) = 8.4$ $8.4 - 6 = 2.4$	+2.4
Add compost, 2 units soil to 1 unit compost, by loose volume	Depth of soil \div 2: $8.4 \div 2 = 4.2$	+4.2
Filling of pore spaces	Depth of loose soil x percentage of pore space filled by compost addition: $8.4 \times (-.15) = -1.3$	-1.3
Rototill compost into soil and roll site to compact soil, assuming compression factor of 1.2	(Amended soil depth \div compression factor) - amended soil depth:	-2.1
Resulting Elevation Change	Sum	+3.2

Turf areas

If the site is well drained and acceptable for traditional lawn installation, then a compost-amended soil lawn will drain equally well while providing superior storm flow storage, pollutant processing, and growth medium (see Section 6.2.4: Performance for details).

If the site being considered for turf establishment does not drain well, an alternative to planting a lawn should be considered. If the site is not freely draining, turf is still being attempted, and maintenance or other activity is required during the wet months, compost amendment will still provide stormwater benefits. However, the ratio of organic matter to soil should be reduced to a maximum of 30 percent by volume. This upper limit is suggested for the Puget Sound region to reduce the spongy feel of soils with high organic matter content and potential compaction during the wet months (Chollak, n.d.). A drainage route or subsurface collection system may be necessary for composted or non-composted turf applications in poorly draining soils.

Steep slopes

WSDOT has been applying compost to condition soils on slopes ranging up to 33 percent since 1992. No stability problems have been observed as a result of the increased water holding capacity of the compost (Chollak, n.d.). Steep slope areas,

which have native soils with healthy native landscapes, should be protected from disturbance. On steep slopes where native soils and vegetation are disturbed or removed, soils should be amended and re-vegetated with deep rooting plants to improve slope stability. Compost can be applied to the ground surface without incorporation to improve plant growth and prevent erosion on steep slopes that cannot be accessed by equipment.

WSDOT has been applying compost to condition soils on slopes ranging up to 33 percent since 1992. No stability problems have been observed as a result of the increased water holding capacity of the compost.

6.2.3 Maintenance

- Incorporate soil amendments at the end of the site development process.
- Protect amended areas from excessive foot traffic and equipment to prevent compaction and erosion.
- Plant and mulch areas immediately after amending soil to stabilize site as soon as possible.
- Minimize or eliminate use of pesticides and fertilizers. Landscape management personnel should be trained to adjust chemical inputs accordingly and manage the landscape areas to minimize erosion, recognize soil and plant health problems, and optimize water storage and soil permeability.

6.2.4 Performance

The surface bulk density of construction site soils generally range from 1.5 to 2.0 gm/cc (CWP, 2000a). At 1.6 to 1.7 gm/cc plant roots cannot penetrate soil and oxygen content, biological activity, nutrient uptake, porosity, and water holding capacity are severely degraded (CWP, 2000a and Balousek, 2003). Tilling alone has limited effect for reducing the bulk density and enhancing compacted soil. A survey of research examining techniques to reverse soil compaction by Schueler found that tilling reduced bulk density by 0.00 to 0.15 gm/cc. In contrast, tilling with the addition of compost amendment decreased bulk density by 0.25 to 0.35 gm/cc (CWP, 2000a).

Balousek (2003) prepared combinations of deep tillage, chisel plow, and compost amended plots on an area with silt loam soil that was cleared and graded to simulate construction site conditions. The deep-tilled plots increased runoff volume compared to the control, and the combined chisel plow and deep-tilled treatment reduced runoff volume by 36 to 53 percent. With compost added to the combined plow and till treatment, runoff volume was reduced by 74 to 91 percent.

Research plots at University of Washington, prepared with various amounts and types of compost mixed with till soil and planted with turf, generated 53 to 70 percent of the runoff volume observed from the unamended control plots. The greatest attenuation was observed in treatments with a ratio of 2 parts soil to 1 part fine, well-aged compost. The study indicates that using compost to amend lawn on till soils can “significantly enhance the ability of the lawn to infiltrate, store and release water as baseflow” (Kolsti, Burges, and Jensen, 1995).

6.3 Permeable Paving

Permeable paving surfaces are designed to accommodate pedestrian, bicycle, and vehicle traffic while allowing infiltration, treatment, and storage of stormwater. The general categories of permeable paving systems include:

- *Open-graded concrete or hot-mix asphalt pavement*, which is similar to standard pavement, but with reduced or eliminated fine material (sand and finer) and special admixtures incorporated (optional). As a result, channels form between the aggregate in the pavement surface and allow water to infiltrate.
- *Aggregate or plastic pavers* that include cast-in-place or modular pre-cast blocks. The cast-in-place systems are reinforced concrete made with reusable forms. Pre-cast systems are either high-strength Portland cement concrete or plastic blocks. Both systems have wide joints or openings that can be filled with soil and grass or gravel.

Permeable paving surfaces accommodate pedestrian, bicycle, and vehicle traffic while allowing infiltration, treatment and storage of stormwater.

- *Plastic grid systems* that come in rolls and are covered with soil and grass or gravel. The grid sections interlock and are pinned in place.

6.3.1 Applications

Typical applications for permeable paving include industrial and commercial parking lots, sidewalks, pedestrian and bike trails, driveways, residential access roads, and emergency and facility maintenance roads. Highways and other high traffic load roads have not been considered appropriate for permeable paving systems. However, porous asphalt has proven structurally sound and remained permeable in a highway application on State Route 87 near Phoenix, Arizona and permeable concrete and pavers have been successfully used in industrial settings with high vehicle loads (Hossain, Scofield and Meier, 1992).



Figure 6.3.1 The residential access road at Jordan Cove Urban Monitoring Project in Connecticut is paved entirely with permeable pavers.

Photo by Tom Wagner

Benefits of permeable pavement

Initial research indicates that properly designed and maintained permeable pavements can virtually eliminate surface flows for low intensity storms common in the Pacific Northwest; store or significantly attenuate subsurface flows (dependent on underlying soil and aggregate storage design); and provide water quality treatment for nutrients, metals, and hydrocarbons (see Section 6.3.4: Performance for additional information).

Permeable paving systems have been designed with aggregate storage to function as infiltration facilities with relatively low subgrade infiltration rates (as low as 0.1 inch/hour). When water is not introduced from adjacent areas, these systems have a lower contribution to infiltration area ratio than conventional infiltration facilities (i.e., 1 to 1) and are less likely to have excessive hydraulic loading. Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. If design constraints require that surface flow be introduced from adjacent areas, particular caution should be taken to ensure that excessive sediment is not directed to the system or that additional flows will not exceed the hydraulic loading capability.

The permeable paving systems examined in this section provide acceptable surfaces for disabled persons. WAC 51-40-1103 Section 1103 (Building Accessibility) states that abrupt changes in height greater than $\frac{1}{4}$ inch in accessible routes of travel shall be beveled to 1 vertical in 2 horizontal. Changes in level greater than $\frac{1}{2}$ inch shall be accomplished with an approved ramp. Permeable asphalt and concrete, while rougher than conventional paving, do not have abrupt changes in level when properly installed. The concrete pavers have small cells filled with aggregate to a level just under the top of the paver, as well as beveled edges. Gravel pave systems use a specific aggregate with a reinforcing grid that creates a firm and relatively smooth surface (see Section 6.3.2: Design).

Two qualifications for use of permeable paving and disabled access should be noted. Sidewalk designs incorporate scoring, or more recently, truncated domes, near the curb ramp to indicate an approaching traffic area for the blind. The rougher surfaces of permeable paving may obscure this transition; accordingly, standard concrete with scoring or concrete pavers with truncated domes should be used for curb ramps (Florida Concrete and Products Association [FCPA], n.d.). Also, the aggregate within the cells of permeable pavers (such as Eco-Stone) can settle or be displaced from vehicle use. As a result, paver installations for disabled parking spaces and walkways may need to include solid pavers. Individual project designs should be tailored to site characteristics and local regulatory requirements.

Many individual products with specific design requirements are available and cannot all be examined in this manual. To present a representative sample of widely applied products, this section will examine the design, installation, maintenance, and performance of permeable hot-mix asphalt, Portland cement concrete, a concrete paver system, and a flexible plastic grid system.

6.3.2 Design

Handling and installation procedures for permeable paving systems are different from conventional pavement. For the successful application of any permeable paving system three general guidelines must be followed.

1. **Correct design specifications**

Proper site preparation, correct aggregate base and wearing course gradations, separation layer, and under-drain design (if included) are essential for adequate infiltration, storage, and release of storm flows, as well as structural integrity. For example, over compaction of the underlying soil and excessive fines present in the base or top course will significantly degrade or effectively eliminate the infiltration capability of the system.

2. **Qualified contractors**

Contractors must be trained and have experience with the product, and suppliers must adhere to material specifications. Installation contractors should provide data showing successful application of product specifications for past projects. If the installation contractor does not have adequate experience the contractor should retain a qualified consultant to monitor production, handling, and placement operations (U.S. Army Corps of Engineers, 2003). Substituting inappropriate materials or installation techniques will likely result in structural or hydrologic performance problems. For example, using vibrating plate compactors (typical concrete installation procedure) with excessive pressures and frequencies will seal the void spaces in permeable cast-in-place concrete.

3. **Sediment and erosion control**

Erosion and introduction of sediment from surrounding land uses should be strictly controlled during and after construction to reduce clogging of the void spaces in the base material and permeable surface. Filter fabric between the underlying soil and base material is required to prevent soil fines from migrating up and into the aggregate base. Muddy construction equipment should not be allowed on the base material or pavement, sediment laden runoff

For successful application of any permeable paving system follow these three general guidelines:

- *Use correct design specifications.*
- *Use qualified contractors.*
- *Strictly control erosion and sediment.*

should be directed to pre-treatment areas (e.g., settling ponds and swales), and exposed soil should be mulched, planted, and otherwise stabilized as soon as possible.

The preceding guidelines are not optional for the installation of permeable paving systems. Past design failures are most often attributed to not adhering to the above general guidelines, and failure is likely without qualified contractors and strict adherence to correct installation specifications.

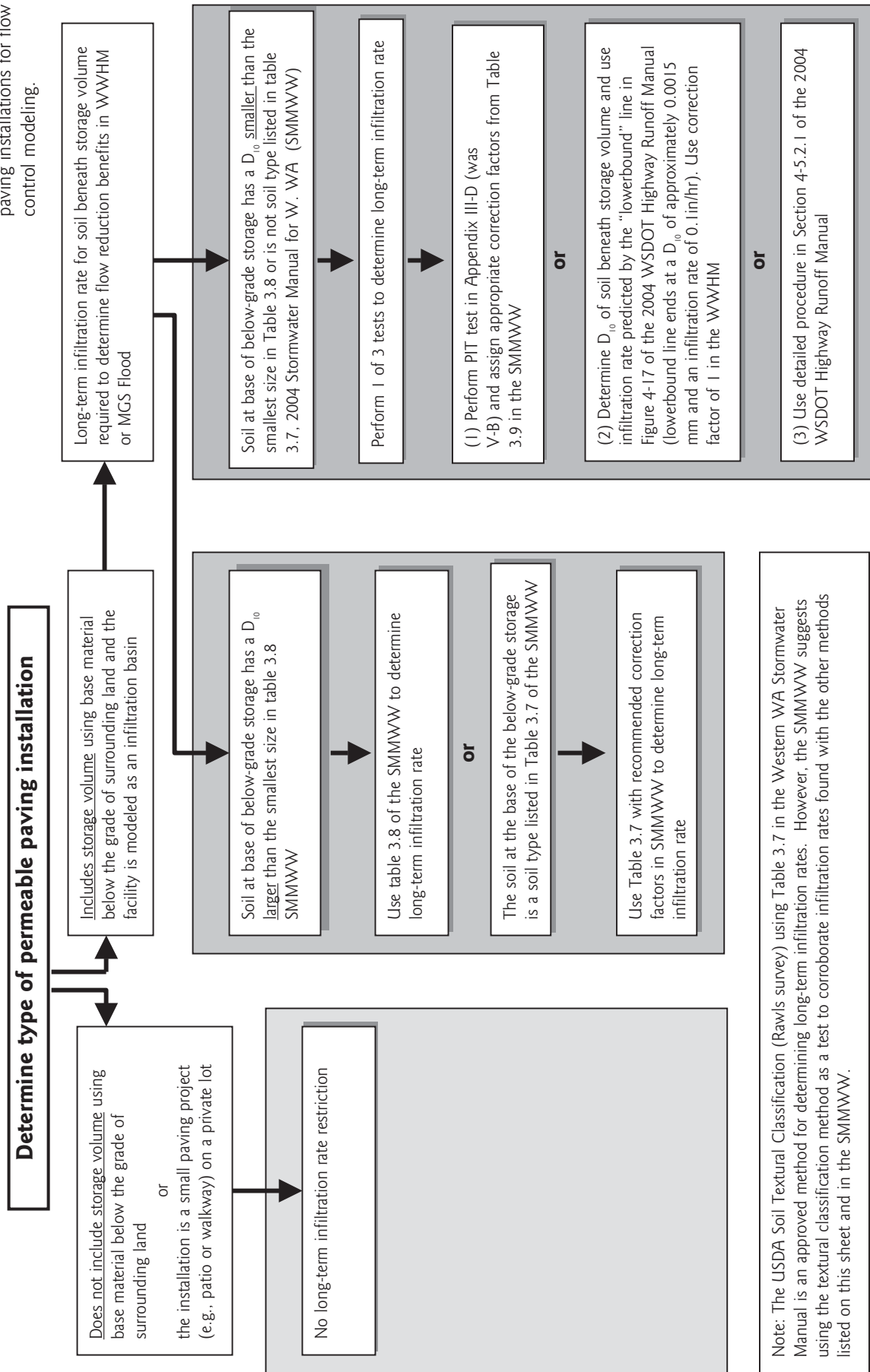
Properly designed permeable paving installations have performed well in the Midwestern and Northeastern U.S. where freeze-thaw cycles are severe (Adams, 2003 and Wei, 1986). Risk of freeze damage can be minimized by extending the base of the permeable paving system to a minimum of half the freeze depth. For example, a total minimum depth for the wearing course and aggregate base material would be 6 inches in the Seattle area, where the freeze-thaw depth is 12 inches (Diniz, 1980).

Determining infiltration rates

Depending on the design, permeable paving installations can be modeled as landscaped area over the underlying soil type or as an infiltration basin. If the installation is modeled as an infiltration basin, determining the infiltration rate of the underlying soil is necessary to equate flow reduction benefits when using the WWHM or MGS Flood. For details on flow modeling guidance see Chapter 7. See Figure 6.3.2 for a graphic representation of the process to determine infiltration rates. The following tests are recommended for soils below the aggregate base material:

- Small permeable paving installations (patios, walkways, and driveways on individual lots): The flow control credits on private property do not include subsurface storage; accordingly, no infiltration field tests are necessary. Soil texture, grain size analysis, or soil pit excavation and infiltration tests may still be prudent if highly variable soil conditions or seasonal high water tables are suspected.
- Large permeable paving installations (sidewalks, alleys, parking lots, roads) that include storage volume using base material below the grade of the surrounding land and the installations are modeled as an infiltration basin:
 - o Method 1: Use USDA Soil Textural Classification (Rawls survey) every 200 feet of road or every 5,000 square feet.
 - o Method 2: Use ASTM D422 Gradation Testing at Full Scale Infiltration Facilities every 200 feet of road or every 5,000 square feet. See the 2005 SMMWW Volume III for details on methods 1 and 2. This method uses the *2004 WSDOT Highway Runoff Manual* protocol.
 - o Method 3: Use small-scale infiltrometer tests every 200 feet of road or every 5,000 square feet. Small-scale infiltrometer tests such as the USEPA Falling Head or double ring infiltrometer tests (ASTM 3385-88) may not adequately measure variability of conditions in test areas. If used, measurements should be taken at several locations within the area of interest.
 - o Method 4: Pilot Infiltration Test (PIT) or small-scale test infiltration pits (septic test pits) at a rate of 1 pit/500 feet of road or 10,000 ft². This infiltration test better represents soil variability and is recommended for highly variable soil conditions or where seasonal high water tables are suspected. See the 2005 SMMWW Appendix III-D (formerly V-B) for PIT method description.

Figure 6.3.2 Determining long-term infiltration rates in soils under permeable paving installations for flow control modeling.



Utility excavations under or beside the road section can provide pits for soil classification, textural analysis, stratigraphy analysis, and/or infiltration tests and minimize time and expense for permeable paving infiltration tests.

Components of permeable paving systems

The following provides a general description and function for the components of permeable paving systems. Design details for specific permeable paving system components are included in the section describing specific types of permeable paving.

Wearing course or surface layer

The wearing course provides compressive and flexural strength for the designed traffic loads while maintaining adequate porosity for storm flow infiltration. Wearing courses include cast-in-place concrete, asphalt, concrete and plastic pavers, and plastic grid systems. In general, permeable top courses have very high initial infiltration rates with various asphalt and concrete research reporting 28 to 1750 inches per hour when new (see Appendix 7: Porous Paving Research for details). Various rates of clogging have been observed in wearing courses and should be anticipated and planned for in the system design (see Section 6.3.5: Performance for research on infiltration rates over time). Permeable paving systems allow infiltration of storm flows; however, the wearing course should not be allowed to become saturated from excessive water volume stored in the aggregate base layer.

Aggregate base

The aggregate base provides: (1) a stable base for the pavement; (2) a highly permeable layer to disperse water downward and laterally to the underlying soil; and (3) a temporary reservoir that stores water prior to infiltration in the underlying soil or collection in under-drains for conveyance (Washington State Department of Transportation [WSDOT], 2003). Base material is often composed of larger aggregate (1.5 to 2.5 inches) with smaller stone (leveling or choker course) between the larger stone and the wearing course. Typical void space in base layers ranges from 20 to 40 percent (WSDOT, 2003 and Cahill, Adams and Marm, 2003). Depending on the target flow control standard and physical setting, retention or detention requirements can be partially or entirely met in the aggregate base. Aggregate base depths of 18 to 36 inches are common depending on storage needs and provide the additional benefit of increasing the strength of the wearing course by isolating underlying soil movement and imperfections that may be transmitted to the wearing course (Cahill et al., 2003).

Separation and water quality treatment layer

The separation layer is a non-woven geotextile fabric that provides a barrier to prevent fine soil particles from migrating up and into the base aggregate. If required, the water quality treatment layer filters pollutants from surface water and protects groundwater quality (generally, a treatment layer will be necessary in critical aquifer recharge areas). The treatment media can consist of a sand layer or an engineered amended soil. Engineered amended soil layers should be a minimum of 18 inches and incorporate compost, sphagnum peat moss or other organic material to provide a **cation exchange capacity** of ≥ 5 milliequivalents/100 grams dry soil (Ecology, 2001). Soil gradation and final mix should provide a minimum infiltration rate of 0.5 inch/hour at final compaction.

Flow modeling guidance

See Chapter 7 for guidance and flow reduction credits for permeable paving systems when using the WWHM.

A treatment layer is not required where the subgrade soil has a long-term infiltration rate of < 2.4 inches/hour and a cation exchange capacity of ≥ 5 milliequivalents/100 grams dry soil.



Figure 6.3.3 Permeable pavers were installed at this Marysville parking lot for infiltration. Organic material was mixed with sand as part of the sub-base to enhance treatment.

Photo by Colleen Owen

Types of permeable paving

The following section provides general design specifications for permeable hot-mix asphalt, Portland cement concrete, a flexible plastic grid system, a cement paver, and a rigid plastic block product. Each product has specific design requirements. Most notably the permeable Portland cement concrete and hot-mix asphalt differ from the paver systems in subgrade preparation. Concrete and asphalt systems are designed and constructed to minimize subgrade compaction and maintain the infiltration capacity of the underlying soils. Paver systems require subgrade compaction to maintain structural support. Some soils with high sand and gravel content can retain useful infiltration rates when compacted; however, many soils in the Puget Sound region become essentially impermeable when compacted to 95 percent modified proctor or proctor rates.

The specifications below are provided to give designers general guidance. Each site has unique characteristics and development requirements; accordingly, qualified engineers and other design disciplines should be consulted for developing specific permeable paving systems.

I. Permeable hot-mix asphalt

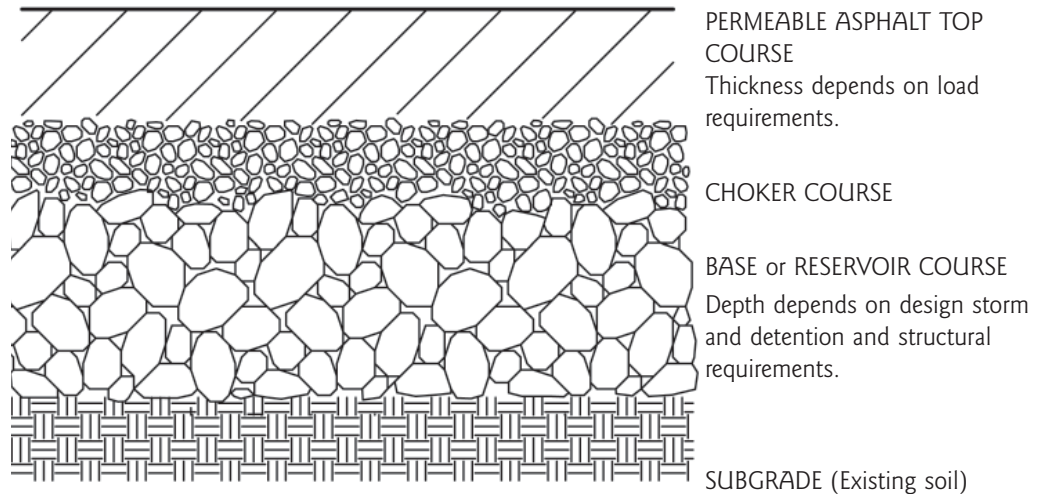
Permeable asphalt is similar to standard hot-mix asphalt; however, the aggregate fines (particles smaller than No. 30 sieve) are reduced, leaving a matrix of pores that conduct water to the underlying aggregate base and soil (Cahill et al., 2003). Porous asphalt can be used for light to medium duty applications including residential access roads, driveways, utility access, parking lots, and walkways; however, porous asphalt has been used for heavy applications such as airport runways (with the appropriate polymer additive to increase bonding strength) and highways (Hossain, Scofield and Meier, 1992). While freeze-thaw cycles are not a large concern in

Properly installed and maintained permeable asphalt should have a service life that is comparable or longer than conventional asphalt.

the Puget Sound lowland, permeable asphalt can and has been successfully installed in wet, freezing conditions in the Midwestern U.S. and Massachusetts with proper section depths (Cahill et al., 2003 and Wei, 1986). Properly installed and maintained permeable asphalt should have a service life that is comparable or longer than conventional asphalt (personal communication, Tom Cahill, 2003).

Figure 6.3.4 Permeable asphalt section.

Graphic by AHBL Engineering



Design

Several permeable bituminous asphalt mixes and design specifications have been developed for friction courses (permeable asphalt layer over conventional asphalt) and as wearing courses that are composed entirely of a porous asphalt mix. The friction courses are designed primarily to reduce noise and glare off standing water at night and hydroplaning; however, this design approach provides minimal attenuation of stormwater during the wet season in the Puget Sound region. The following provides specifications and installation procedures for permeable asphalt applications where the wearing top course is entirely porous, the base course accepts water infiltrated through the top course, and the primary design objective is to significantly or entirely attenuate storm flows.

Application: parking lots, driveways, and residential and utility access roads.

Soil infiltration rate

- As long as runoff is not directed to the permeable asphalt from adjacent surfaces, the estimated long-term infiltration rate may be as low as 0.1 inch/hour. Soils with lower infiltration rates should have under-drains to prevent prolonged saturated soil conditions at or near the ground surface within the pavement section.
- Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. Surface flows from adjacent areas can introduce excess sediment, increase clogging, and result in excessive hydrologic loading. However, it may be acceptable to direct flows after treatment to the subgrade if storage volume and infiltration rates allow.

Subgrade

- Soil conditions should be analyzed by a qualified engineer for load bearing given anticipated soil moisture conditions.

- After grading, the existing subgrade should not be compacted or subjected to excessive construction equipment traffic.
- If using the base course for retention in parking areas, excavate the storage bed level to allow even distribution of water and maximize infiltration across entire parking area.
- Immediately before base aggregate and asphalt placement, remove any accumulation of fine material from erosion with light equipment and scarify soil to a minimum depth of 6 inches.

Aggregate base/storage bed

- Minimum base depth for structural support should be 6 inches (Washington State Department of Transportation, 2003).
- Maximum depth is determined by the extent to which the designer intends to achieve a flow control standard with the use of a below-grade storage bed. Aggregate base depths of 18 to 36 inches are common depending on storage needs.
- Coarse aggregate layer should be a 2.5- to 0.5-inch uniformly graded crushed (angular) thoroughly washed stone (AASHTO No. 3).
- Choker course should be 1 to 2 inches in depth and consist of 1.5-inch to U.S. sieve size number 8 uniformly graded crushed washed stone for final grading of base reservoir. The upper course is needed to reduce rutting from construction vehicles delivering and installing asphalt and to more evenly distribute loads to the base material (Diniz, 1980).

Installation of Aggregate base/storage bed

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- Install approved non-woven filter fabric on subsoil according to manufacturer's specifications. Where installation is adjacent to conventional paving surfaces, filter fabric should be wrapped up sides to top of base aggregate to prevent migration of fines from densely graded material to the open graded base, maintain proper compaction, and avoid differential settling.
- Overlap adjacent strips of fabric at least 24 inches. Secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of area storage reservoir.
- Install coarse (1.5 to 2.5 inch) aggregate in maximum of 8-inch lifts and lightly compact each lift.
- Install a 1 to 2-inch choker course evenly over surface of coarse aggregate base.
- Following placement of base aggregate and again after placement of the asphalt, the filter fabric should be folded over placements to protect installation from sediment inputs. Excess filter fabric should not be trimmed until site is fully stabilized (U.S. Army Corps of Engineers, 2003).

Top course

- Parking lots: 2 to 4 inches typical.
- Residential access roads: 2 to 4 inches typical.
- Permeable asphalt has similar strength and flow properties as conventional asphalt; accordingly, the wearing course thickness is similar for either surface given equivalent load requirements (Diniz, 1980).

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	1/2	100
	3/8	92-98
	4	32-38
	8	12-18
	16	7-13
	30	0-5
	200	0-3

- A small percentage of fine aggregate is necessary to stabilize the larger porous aggregate fraction. The finer fraction also increases the viscosity of the asphalt cement and controls asphalt drainage characteristics.
- Total void space should be approximately 16 percent (conventional asphalt is 2 to 3 percent) (Diniz, 1980).

Bituminous asphalt cement

- Content: 5.5 to 6.0 percent by weight dry aggregate. The minimum content assures adequate asphalt cement film thickness around the aggregate to reduce photo-oxidation degradation and increase cohesion between aggregate. The upper limit is to prevent the mixture from draining during transport.
- Grade: 85 to 100 penetration recommended for northern states (Diniz, 1980).
- An elastomeric polymer can be added to the bituminous asphalt to reduce drain-down.
- Hydrated lime can be added at a rate of 1.0 percent by weight of the total dry aggregate to mixes with granite stone to prevent separation of the asphalt from the aggregate and improve tensile strength.

General installation

- Install permeable asphalt system toward the end of construction activities to minimize sediment problems. The subgrade can be excavated to within 6 inches of final grade and grading completed in later stages of the project (Cahill et al., 2003).
- Erosion and introduction of sediment from surrounding land uses should be strictly controlled during and after construction. Erosion and sediment controls should remain in place until area is completely stabilized with soil amendments and landscaping.
- Adapting aggregate specifications can influence bituminous asphalt cement properties and permeability of the asphalt wearing course. Before final installation, test panels are recommended to determine asphalt cement grade and content compatibility with the aggregate (Diniz, 1980).
- Insulated covers over loads during hauling can reduce heat loss during transport and increase working time (Diniz, 1980). Temperatures at delivery that are too low can result in shorter working times, increased labor for hand work, and increased cleanup from asphalt adhering to machinery (personal communication Leonard Spodoni, April 2004).

Backup systems for protecting permeable asphalt systems

- For backup infiltration capacity (in case the asphalt top course becomes clogged) an unpaved stone edge can be installed that is hydrologically connected to the storage bed (see Figure 6.3.5).

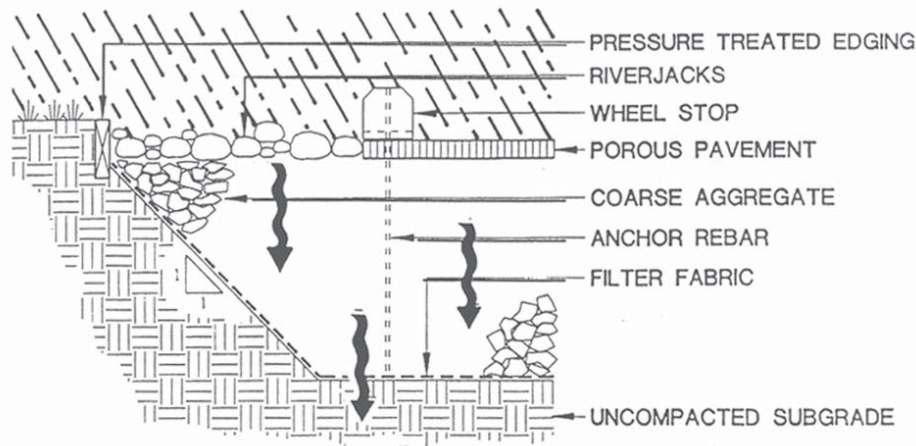


Figure 6.3.5 Unpaved section (river jacks) provides backup infiltration.

Graphic courtesy of Cahill Associates

- As with any paving system, rising water in the underlying aggregate base should not be allowed to saturate the pavement (Cahill et al., 2003). To ensure that the asphalt top course is not saturated from excessively high water levels in the aggregate base (as a result of subgrade soil clogging), a positive overflow can be installed.

For a sample specification for permeable asphalt paving see Appendix 8.

Cost

Materials and mixing costs for permeable asphalt are similar to conventional asphalt. In general, local contractors are currently not familiar with permeable asphalt installation, and additional costs for handling and installation should be anticipated. Estimates for porous pavement material and installation are approximately \$.60 to .70/square foot and will likely be comparable to standard pavement as contractors become more familiar with the product. Due to the lack of experience regionally, this is a rough estimate. The cost for base aggregate will vary significantly depending on base depth for stormwater storage and is not included in the cost estimate.

2. Portland cement permeable concrete

Florida and Georgia use permeable concrete extensively for stormwater management. The material and installation specifications in Washington are derived primarily from the field experience and testing through the Florida Concrete and Products Association. In the Puget Sound region, the cities of Seattle and Olympia and Stoneway Concrete have tested materials and installed several projects including parking lots, sidewalks, and driveways.

Permeable Portland cement concrete is similar to conventional concrete without the fine aggregate (sand) component. The mixture is a washed coarse aggregate (3/8 or 5/8 inch), hydraulic cement, admixtures (optional) and water, yielding a surface with a matrix of pores that conducts water to the underlying aggregate base and soil. Permeable concrete can be used for light to medium duty applications including residential access roads, driveways, utility access, parking lots, and walkways. Permeable concrete can also be used in heavy load applications. For example, test sections in a city of Renton aggregate recycling yard have performed well

structurally after being subjected to regular 50,000- to 100,000-pound vehicle loads for the past three years (personal communication, Greg McKinnon, March 2004). Properly installed and maintained concrete should have a service life comparable to conventional concrete.

Designing the aggregate base to accommodate retention or detention storage will depend on several factors, some of which include project specific stormwater flow control objectives, costs, and regulatory restrictions. However, deeper subgrade to base courses (e.g., 12 to 36 inches) can provide important benefits including significant reduction of above ground stormwater retention or detention needs and uniform subgrade support (FCPA, n.d.). Base courses that are placed above the surrounding grade cannot be used, or given credit for, reducing retention or detention pond sizes. (See Chapter 7 for flow modeling guidance and flow reduction credits.)

Figure 6.3.6 Permeable concrete adjacent to stamped concrete in Des Moines.

Photo by Curtis Hinman



Design and installation

Three general classes of permeable concrete are prevalent: (1) the standard mix using washed coarse aggregate (3/8 or 5/8 inch), hydraulic cement, admixtures (optional) and water; (2) a Stoneycrrete mixture which is similar to the standard mix, but incorporates a strengthening additive; and (3) Percocrete which uses a higher percentage of sand, incorporates an additive to enhance strength and the pore structure, and produces a smoother surface texture. The following design section examines the standard concrete mix. Additional information for Stoneycrrete is available at Stoney Creek Materials L.L.C. Austin, Texas and for Percocrete at Michiels International Inc., Kenmore, Washington.

Application: parking lots, driveways, sidewalks, utility access, and residential roads.

Soil infiltration rate

- If runoff is not directed to the permeable concrete from adjacent surfaces, the estimated long-term infiltration rate may be as low as 0.1 inch/hour. Soils with lower infiltration rates should have under-drains to prevent prolonged saturated soil conditions at or near the ground surface within the pavement section.
- Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. Surface flows from adjacent areas can introduce excess sediment, increase clogging, and result in excessive hydrologic loading.

However, it may be acceptable to direct flows after treatment to the subgrade if storage volume and infiltration rates allow.

Subgrade

- Soil conditions should be analyzed for load bearing given anticipated soil moisture conditions by a qualified engineer.
- After grading, the existing subgrade should not be compacted or subject to excessive construction equipment traffic (U.S. Army Corps of Engineers, 2003).
- Immediately before base aggregate and concrete placement, remove any accumulation of fine material from erosion with light equipment and scarify soils to a minimum depth of 6 inches if compacted (U.S. Army Corps of Engineers, 2003).

Aggregate base/storage bed

- Minimum base depth for structural support should be 6 inches (FCPA, n.d.).
- Maximum depth is determined by the extent to which the designer intends to achieve a flow control standard with the use of a below-grade storage bed. Aggregate base depths of 18 to 36 inches are common when designing for retention or detention.
- The coarse aggregate layer varies depending on structural and stormwater management needs. Typical placements include round or crushed washed drain rock (1 to 1.5 inches) or 1.5 to 2.5-inch crushed washed base rock aggregate (e.g., AASTHO No. 3).
- The concrete can be placed directly over the coarse aggregate or a choker course (e.g., 1.5 inch to US sieve size number 8, AASHTO No 57 crushed washed stone) can be placed over the larger stone for final grading.

Installation of aggregate base/storage bed

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- If using the aggregate base for retention in parking areas, excavate storage bed level to allow even distribution of water and maximize infiltration across entire parking area.
- Install approved non-woven filter fabric on subsoil according to manufacturer's specifications. Where concrete installations are adjacent to conventional paving surfaces the filter fabric should be wrapped up the sides and to the top of base aggregate to prevent migration of fines from the densely graded base to the open graded base material, maintain proper compaction, and avoid differential settling.
- Overlap adjacent strips of fabric at least 24 inches. Secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of storage reservoir.
- Install coarse aggregate in maximum of 8-inch lifts and lightly compact each lift (U.S. Army Corps of Engineers, 2003).
- If utilized, install a 1-inch choker course evenly over surface of coarse aggregate base (typically No. 57 AASHTO) and lightly compact.
- Following placement of base aggregate and again after placement of concrete, the filter fabric should be folded over placements to protect installation from sediment inputs. Excess filter fabric should not be trimmed until site is fully stabilized (U.S. Army Corps of Engineers, 2003).

Top course

- Parking lots: 4 inches typical.
- Roads: 6 to 12 inches typical.
- Unit weight: 120 to 130 pounds per cubic foot (permeable concrete is approximately 70 to 80 percent of the unit weight of conventional concrete) (FCPA, n.d.).
- Void space: 15 to 21 percent according to ASTM C 138.
- Water cement ratio: 0.27 to 0.35.
- Aggregate to cement ratio: 4:1 to 4.5:1.
- Aggregate: several aggregate specifications are used including:
 - 3/8-inch to No. 16 washed crushed or round per ASTM C 33.
 - 3/8-inch to No. 50 washed crushed or round per ASTM D 448.
 - 5/8-inch washed crushed or round.
 - In general the 3/8-inch crushed or round produces a slightly smoother surface and is preferred for sidewalks, and the 5/8-inch crushed or round produces a slightly stronger surface.
- Portland cement: Type I or II conforming to ASTM C 150 or Type IP or IS conforming to ASTM C 595.
- Admixtures: Can be used to increase working time and include: Water Reducing/Retarding Admixture in conformance with ASTM C 494 Type D and Hydration stabilizer in conformance with ASTM C 494 Type B.
- Water: Use potable water.
- Fiber mesh can be incorporated into the cement mix for added strength.

Installation of top course

- See testing section below for confirming correct mixture and proper installation.
- If mixture contains excess water the cement paste can flow from the aggregate, resulting in a weak surface layer and reduced void space in the lower portion of surface. With the correct water content, the delivered mix should have a wet metallic sheen, and when hand squeezed the mix should not crumble or become a highly plastic mass (FCPA, n.d.).
- Cement mix should be used within 1 hour after water is introduced to mix, and within 90 minutes if an admixture is used and concrete mix temperature does not exceed 90 degrees Fahrenheit (U.S. Army Corps of Engineers, 2003).
- Base aggregate should be wetted to improve working time of cement.
- Concrete should be deposited as close to its final position as possible and directly from the truck or using a conveyor belt placement.
- A manual or mechanical screed can be used to level concrete at 1/2 inch above form.
- Cover surface with 6-mil plastic and use a static drum roller for final compaction (roller should provide approximately 10 pounds per square inch vertical force).
- Edges that are higher than adjacent materials should be finished or rounded off to prevent chipping (standard edging tool is applicable for pervious concrete).
- Cement should be covered with plastic within 20 minutes and remain covered for curing time.
- Curing: 7 days minimum for Portland cement Type I and II. No truck traffic should be allowed for 10 days (U.S. Army Corps of Engineers, 2003).

- Placement widths should not exceed 15 feet unless contractor can demonstrate competence to install greater widths.
- High frequency vibrators can seal the surface of the concrete and should not be used.
- Jointing: Shrinkage associated with drying is significantly less for permeable than conventional concrete. Florida installations with no control joints have shown no visible shrink cracking. A conservative design can include control joints at 60 foot spacing cut to 1/4 the thickness of the pavement (FCPA, n.d. and U.S. Army Corps of Engineers, 2003). Expansion joints can also facilitate a cleaner break point if sections become damaged or are removed for utility work.

Testing

Differences in local materials, handling, and placement can affect permeable concrete performance. The following tests should be conducted even if the contractor or consultant has experience with the material to ensure proper performance.

- The contractor should place and cure two test panels, each covering a minimum of 225 square feet at the required project thickness, to demonstrate that specified unit weights and permeability can be achieved on-site (Georgia Concrete and Products Association [GCPA], 1997).
- Test panels should have two cores taken from each panel in accordance with ASTM C 42 at least 7 days after placement (GCPA, 1997).
- Untrimmed cores should be measured for thickness according to ASTM C 42.
- After determining thickness, cores should be trimmed and measured for unit weight per ASTM C 140.
- Void structure should be tested per ASTM C 138.
- If the measured thickness is greater than 1/4 inch less than the specified thickness, or the unit weight is not within ± 5 pounds per cubic foot, or the void structure is below specifications, the panel should be removed and new panels with adjusted specifications installed (U.S. Army Corps of Engineers, 2003). If test panel meets requirements, panel can be left in place as part of the completed installation.
- Collect and sample delivered material once per day to measure unit weight per ASTM C 172 and C 29 (FCPA, n.d.).

Backup systems for protecting permeable concrete systems

- For backup infiltration capacity (in case the concrete top course becomes clogged) an unpaved stone edge can be installed that is connected to the base aggregate storage reservoir (see Figure 6.3.5).
- As with any paving system, rising water in the underlying aggregate base should not be allowed to saturate the pavement (Cahill et al., 2003). To ensure that the top course is not saturated from excessively high water levels (as a result of subgrade soil clogging), a positive overflow can be installed in the base.

Cost

Permeable concrete material and installation is approximately \$3.00 to \$5.00 per square foot depending on surface thickness and site conditions. Cost for base aggregate will vary significantly depending on base depth for stormwater storage and is not included in the cost estimate.

3. Eco-Stone permeable interlocking concrete pavers

Eco-Stone is a high-density concrete paver that allows infiltration through a built-in pattern of openings filled with aggregate. When compacted, the pavers interlock and transfer vertical loads to surrounding pavers by shear forces through fine aggregate in the joints (Pentec Environmental, 2000). Eco-Stone interlocking pavers are placed on open graded sub-base aggregate topped with a finer aggregate layer that provides a level and uniform bedding material. Properly installed and maintained, high-density pavers have high load bearing strength and are capable of carrying heavy vehicle weight at low speeds. Properly installed and maintained pavers should have a service life of 20 to 25 years (Smith, 2000).

Figure 6.3.7 Permeable interlocking concrete paver section.

Graphic by Gary Anderson

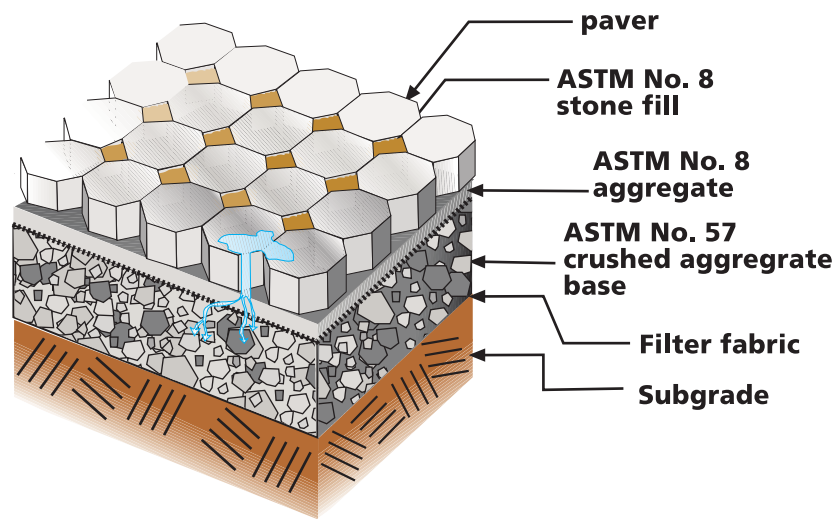


Figure 6.3.8 Close-up view of permeable pavers.

Photo by Curtis Hinman



Design

Application: Industrial and commercial parking lots, utility access, residential access roads, driveways, and walkways. Experienced contractors with a current certificate in the ICPI Contractor Certification Program should perform installations.

Soil infiltration rate

- If runoff is not directed to the permeable pavers from adjacent surfaces, the estimated long-term infiltration rate may be as low as 0.5 inch/hour. Soils with lower infiltration rates should have under-drains at the bottom of the base course to prevent prolonged saturated soil conditions at or near the ground surface within the pavement section. Drain-down time for the base should not exceed 24 hours.
- Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. Surface flows from adjacent areas can introduce excess sediment, increase clogging, and result in excessive hydrologic loading. However, it may be acceptable to direct flows after treatment to the subgrade if storage volume and infiltration rates allow.

Subgrade

- Soils should be analyzed by a qualified engineer for infiltration rates and load bearing, given anticipated soil moisture conditions. **California Bearing Ratio** values should be at least 5 percent.
- For vehicle traffic areas, grade and compact to 95 percent modified proctor density (per ASTM D 1557) and compact to 95 percent standard proctor density for pedestrian areas (per ASTM D698) (Smith, 2000). Soils with high sand and gravel content can retain useful infiltration rates when compacted; however, many soils in the Puget Sound region become essentially impermeable at this compaction rate. For detention designs on compacted soils that will provide very low permeability, adequate base aggregate depths and under-drain systems should be incorporated to reduce risk of continued saturation that can weaken subgrades subject to vehicle traffic (Smith, 2000).

Aggregate base/storage bed

- Minimum base thickness depends on vehicle loads, soil type, stormwater storage requirements, and freeze thaw conditions. Typical depths range from 6 to 22 inches; however, increased depths can be applied for increased storage capacity (Smith, 2000). Interlocking Concrete Paver Institute guidelines for base thickness should be followed.
- Minimum base depth for pedestrian and bike applications should be 6 inches (Smith, 2000).
- ASTM No. 57 crushed aggregate or similar gradation is recommended for the sub-base (Smith, 2000).
- ASTM No. 8 is recommended for the leveling or choker course.

Installation of aggregate base/storage bed

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- If using the base course for retention in parking areas, excavate storage bed level to allow even distribution of water and maximize infiltration across entire parking area.

- Install approved non-woven filter fabric to bottom and sides of excavation according to manufacturer's specifications. Where paver installation is adjacent to conventional paving surfaces, filter fabric should be wrapped up sides to top of base aggregate to prevent migration of fines from densely graded base to the open graded base material, maintain proper compaction, and avoid differential settling. A concrete curb the depth of the base can also be used to separate the open graded and dense graded bases.
- Overlap adjacent strips of fabric at least 24 inches. Secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of area storage reservoir (Smith, 2000).
- Install No. 57 aggregate in 4 to 6-inch lifts.
- Compact the moist No. 57 aggregate with at least 4 passes of a 10-ton (minimum) steel drum roller. Initial passes can be with vibration and the final two passes should be static (Smith, 2000). Testing for appropriate density per ASTM D 698 or D 1557 will likely not provide accurate results. The Interlocking Concrete Pavement Institute specification recommends that adequate density and stability are developed when no visible movement is observed in the open-graded base after compaction (personal communication, Dave Smith ICPI).
- Install three inches of No. 8 aggregate for the leveling or choker course and compact with at least 4 passes of a 10-ton roller. Surface variation should be within $\pm 1/2$ inch over 10 feet. The No. 8 aggregate should be moist to facilitate compaction into the sub-base (Smith, 2000).
- Asphalt stabilizer can be used with the No. 57 stone if additional bearing support is needed, but should not be applied to the No. 8 aggregate. To maintain adequate void space, use a minimum of asphalt for stabilization (approximately 2 to 2.5 percent by weight of aggregate). An asphalt grade of AC20 or higher is recommended. The addition of stabilizer will reduce storage capacity of base aggregate and should be considered in the design (Smith, 2000).
- Following placement of base aggregate and again after placement of pavers, the filter fabric should be folded over placements to protect installation from sediment inputs. Excess filter fabric should not be trimmed until site is fully stabilized.
- Designs for full infiltration of stormwater to the subgrade should have a positive overflow to prevent water from entering the surface layer during extreme events. Designs with partial or no **exfiltration** require under-drains. All installations should have an observation well (typically 6-inch perforated pipe) installed at the furthest downslope area (Smith, 2000).

Top course installation

- Pavers should be installed immediately after base preparation to minimize introduction of sediment and to reduce the displacement of base material from ongoing activity (Smith, 2000).
- Loosen and evenly smooth $3/4$ to 1 inch of the compacted No. 8 stone.
- Place pavers by hand or with mechanical installers and compact with a 5000 lbf, 75 to 90 Hz plate compactor. Fill openings with No. 8 stone and compact again. Sweep to remove excess stone from surface. The small amount of finer aggregate in the No. 8 stone will likely be adequate to fill narrow joints between pavers in pedestrian and light vehicle applications. If the installation is subject

to heavy vehicle loads, additional material may be required for joints. Sweep in additional material (ASTM No. 89 stone is recommended) and use vibratory compaction to place joint material (Smith, 2000).



Figure 6.3.9 Mechanical installation of Eco-Stone pavers.

Photo by Curtis Hinman

- Do not compact within 3 feet of unrestrained edges (Pentec Environmental, 2000).
- Sand placed in paver openings or used as a leveling course will clog and should not be applied for those purposes.
- Cast-in-place or pre-cast concrete (approximately 6 inches wide by 12 inches high) are the preferred material for edge constraints. Plastic edge confinement secured with spikes is not recommended (Smith, 2000).

Cost

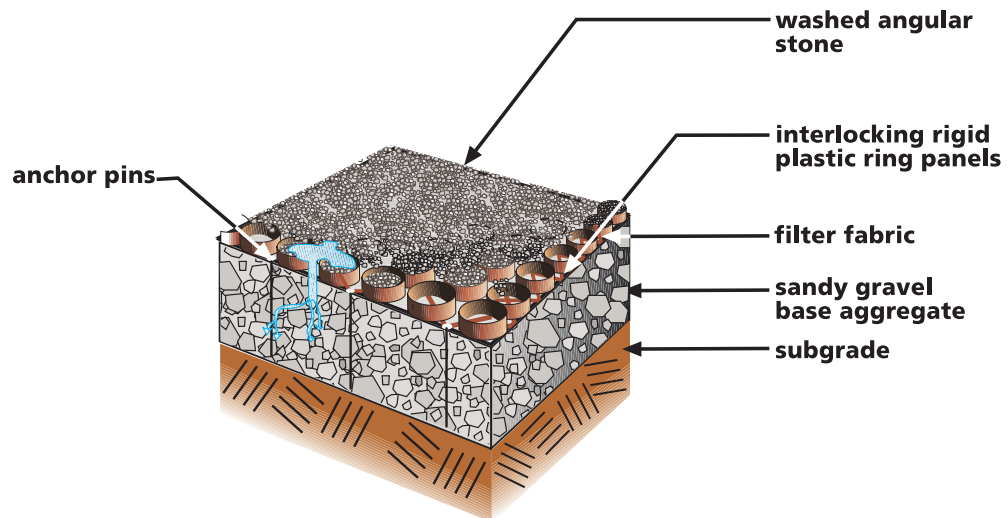
Eco-Stone material and installation costs range from \$2.50 to \$4.50 per square foot for the pavers, aggregate leveling layer, aggregate for the paver openings and joints, and installation. Costs for base aggregate will vary significantly depending on stormwater storage needs. Base material and installation, geotextile, excavation, and sediment controls are not included in this price estimate. Large jobs (e.g., 150,000 square feet) utilizing mechanical placement of pavers would qualify for the lower end of the cost range and smaller jobs (e.g., 40,000 square feet) with mechanical installation would likely be at the higher end of the cost range (personal communication, Brian Crooks and Dave Parisi, July 2004).

4. Gravelpave2 flexible plastic grid system

Gravelpave2 is a lightweight grid of plastic rings in 20" wide x 20" long x 1" high units with a geotextile fabric heat fused to the bottom of the grid. The grid and fabric is provided in pre-assembled rolls of various dimensions (Invisible Structures, 2003). This and other similar plastic grid systems have a large amount of open cell available for infiltration in relation to the solid support structure. Flexible grid systems conform to the grade of the aggregate base, and when backfilled with appropriate aggregate top course, provide high load bearing capability (Gravelpave2 load capacity is approximately 5700 psi) (Invisible Structures, 2003). Gravelpave2 is not impacted by the degree of freeze-thaw conditions found in the Puget Sound region. Properly installed and maintained, Gravelpave2 has an expected service life of approximately 20 years (Bohnhoff, 2001).

Figure 6.3.10 Gravelpave2 system.

Graphic by Gary Anderson



Design

Application: Typical uses include alleys, driveways, utility access, loading areas, trails, and parking lots with relatively low traffic speeds (15 to 20 mph maximum). Higher speeds may require use of a binder at 10 percent cement by weight with fill stone (Bohnhoff, 2001).

Soil infiltration rate

- If runoff is not directed to the Gravelpave system from adjacent surfaces, the estimated long-term infiltration rate may be as low as 0.5 inch/hour. Soils with lower infiltration rates should have under-drains in the base course to prevent prolonged saturated soil conditions within the top course section.
- Directing surface flows to permeable paving surfaces from adjacent areas is not recommended. Surface flows from adjacent areas can introduce excess sediment, increase clogging, and result in excessive hydrologic loading. However, it may be acceptable to direct flows after treatment to the subgrade if storage volume and infiltration rates allow.

Subgrade

- Soil conditions should be analyzed for load bearing given anticipated soil moisture conditions by a qualified engineer.
- After grading, the existing subgrade should not be compacted or subject to excessive construction equipment traffic.
- Immediately before base aggregate and top course, remove any accumulation of fine material from erosion with light equipment.

Aggregate base/storage bed

- Minimum base thickness depends on vehicle loads, soil type, and stormwater storage requirements. Typical minimum depth is 4 to 6 inches for driveways, alleys, and parking lots (less base course depth is required for trails) (personal communication, Andy Gersen, July 2004). Increased depths can be applied for increased storage capacity.

- Base aggregate is a sandy gravel material typical for road base construction (Invisible Structures, 2003).

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	3/4	100
	3/8	85
	4	60
	8	15
	40	30
	200	<3

Base course installation

- Stabilize area and install erosion control to prevent runoff and sediment from entering storage bed.
- If using the base course for retention in parking areas, excavate storage bed level to allow even distribution of water and maximize infiltration across entire parking area.
- Install approved non-woven filter fabric to bottom and sides of excavation according to manufacturer's specifications. Where the installation is adjacent to conventional paving surfaces, the filter fabric should be wrapped up the sides and to the top of base aggregate to prevent migration of fines from the densely graded base to the open graded base aggregate, maintain proper compaction, and avoid differential settling.
- Overlap adjacent strips of fabric at least 24 inches. Secure fabric 4 feet outside of storage bed to reduce sediment input to bottom of area storage reservoir.
- Install aggregate in 6-inch lifts maximum.
- Compact each lift to 95 percent modified proctor.

Top course aggregate

Aggregate should be clean, washed angular stone with a granite hardness.

Aggregate grading:	U.S. Standard Sieve	Percent Passing
	4	100
	8	80
	16	50
	30	30
	50	15
	100	5

Top course installation

- Grid should be installed immediately after base preparation to minimize introduction of sediment and to reduce the displacement of base material from ongoing activity.
- Place grid with rings up and interlock male/female connectors along unit edges.
- Install anchors at an average rate of 6 pins per square meter. Higher speed and transition areas (for example where vehicles enter a parking lot with a plastic grid system from an asphalt road) or where heavy vehicles execute tight turns will require additional anchors (double application of pins).
- Aggregate should be back dumped to a minimum depth of 6 inches so that delivery vehicle exits over aggregate. Sharp turning on rings should be avoided.

- Spread gravel using power brooms, flat bottom shovels or wide asphalt rakes. A stiff bristle broom can be used for finishing.
- If necessary, aggregate can be compacted with a plate compactor to a level no less than the top of the rings or no more than 0.25 inch above the top of the rings (Invisible Structures, 2003).
- Provide edge constraints along edges that may have vehicle loads (particularly tight radius turning). Cast-in-place or pre-cast concrete edging is preferred.

6.3.3 Maintenance

The following provides maintenance recommendations applicable to all permeable paving surfaces.

- Erosion and introduction of sediment from surrounding land uses should be strictly controlled after construction by amending exposed soil with compost and mulch, planting exposed areas as soon as possible, and armoring outfall areas.
- Surrounding landscaped areas should be inspected regularly and possible sediment sources controlled immediately.
- Clean permeable paving surfaces to maintain infiltration capacity once or twice annually following maintenance recommendations under each paving type.
- Utility cuts should be backfilled with the same aggregate base used under the permeable paving to allow continued conveyance of stormwater through the base, and to prevent migration of fines from the standard base aggregate to the more open graded permeable base material (Diniz, 1980).

The following provides maintenance recommendations for specific permeable paving surfaces.

- Permeable asphalt and concrete
 - o Clean surfaces using suction, sweeping with suction or high-pressure wash and suction (sweeping alone is minimally effective). Street cleaning equipment using high-pressure wash with suction provides the best results on asphalt and concrete for improving infiltration rates. However, there are currently no high-pressure wash and suction machines for cleaning pavement in the U.S. The city of Olympia will be importing the first machine of this type and expects delivery early 2005 (personal communication, Mark Blosser, July 2004). Hand held pressure washers are effective for cleaning void spaces and appropriate for smaller areas such as sidewalks.
 - o Small utility cuts can be repaired with conventional asphalt or concrete if small batches of permeable material are not available or are too expensive.
- Eco-Stone permeable pavers
 - o Washing should not be used to remove debris and sediment in the openings between the pavers. Sweeping with suction can be applied to paver openings when surface and debris are dry. Vacuum settings may have to be adjusted to prevent excess uptake of aggregate from paver openings or joints (Smith, 2000).
 - o Pavers can be removed individually and replaced when utility work is complete.
 - o Replace broken pavers as necessary to prevent structural instability in the surface.

- o The structure of the top edge of the paver blocks reduces chipping from snowplows. For additional protection, skids on the corner of plow blades are recommended.
- Gravelpave2
 - o Remove and replace top course aggregate if clogged with sediment or contaminated (vacuum trucks for stormwater collection basins can be used to remove aggregate).
 - o Remove and replace grid segments where three or more adjacent rings are broken or damaged.
 - o Replenish aggregate material in grid as needed.
 - o Snowplows should use skids to elevate blades slightly above the gravel surface to prevent loss of top course aggregate and damage to plastic grid.

6.3.4 Limitations

Permeable paving materials are not recommended where:

- Excessive sediment is deposited on the surface (e.g., construction and landscaping material yards).
- Steep erosion prone areas that are likely to deliver sediment and clog pavement are upslope of the permeable surface.
- Concentrated pollutant spills are possible such as gas stations, truck stops, and industrial chemical storage sites.
- Seasonally high groundwater creates prolonged saturated conditions at or near ground surface and within the pavement section.
- Fill soils can become unstable when saturated.
- Maintenance is unlikely to be performed at appropriate intervals.
- Sealing of surface from sealant application or other uncontrolled use is likely. Residential driveways can be particularly challenging and clear, enforceable guidelines, education, and backup systems should be part of the stormwater management plan for a residential area utilizing permeable paving for driveways.
- Regular, heavy application of sand is used for maintaining traction during winter.
- Permeable paving should not be placed over solid rock without an adequate layer of aggregate base.

Slope restrictions result primarily from flow control concerns and to a lesser degree structural limitations of the permeable paving. Excessive gradient increases surface and subsurface flow velocities and reduces storage and infiltration capacity of the pavement system. Baffle systems placed on the subgrade can be used to detain subsurface flow and increase infiltration (personal communication, Tracy Tackett). See Chapter 7 for the flow control credit associated with permeable paving and subgrade baffles.

- Permeable asphalt is not recommended for slopes exceeding 5 percent.
- Permeable concrete is not recommended on slopes exceeding 6 percent.
- Eco-Stone is not recommended for slopes exceeding 10 percent.
- Gravelpave2 is not recommended for slopes exceeding 6 percent (primarily a traction rather than infiltration or structural limitation).

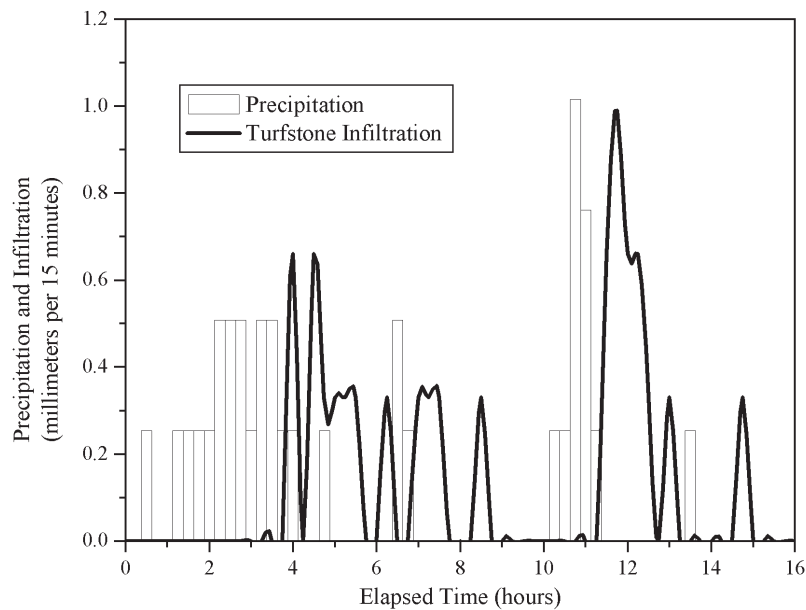
6.3.5 Permeable Paving Performance

Infiltration

Initial research indicates that properly designed and maintained permeable pavements can virtually eliminate surface flows for low intensity storms common in the Pacific Northwest, store or significantly attenuate subsurface flows (dependent on underlying soil and aggregate storage design), and provide water quality treatment for nutrients, metals, and hydrocarbons. A six-year University of Washington permeable pavement demonstration project found that nearly all water infiltrated various test surfaces (included Eco-Stone, Gravelpave, and others) for all observed storms (Brattebo and Booth, 2003). Observed infiltration was high despite minimal maintenance conducted. See Figure 6.3.11 for infiltration plotted with precipitation for one of the permeable paving test surfaces (turfstone).

Figure 6.3.11 Infiltration plotted with precipitation at a test permeable pavement parking stall in the city of Renton. Note that essentially all precipitation infiltrates.

Source: Brattebo and Booth, 2003



Initial infiltration rates for properly installed permeable pavement systems are high. Infiltration rates for in-service surfaces decline to varying degrees depending on numerous factors, including initial design and installation, sediment loads, and maintenance. Ranges of new and in-service infiltration rates for research cited in the Appendix 7: Porous Paving Research are summarized below. To provide context for the infiltration rates below, typical rainfall rates are approximately 0.05 inch/hour in the Puget Sound region with brief downpours of 1 to 2 inches/hour.

Porous asphalt: highest initial rate (new installation): 1750 in/hr
lowest initial rate (new installation): 28 in/hr
highest in-service rate: 1750 in/hr (1 year of service, no maintenance)
lowest in-service rate: 13 in/hr (3 years of service no maintenance)

Pervious concrete: highest initial rate: 1438.20 in/hr
lowest in-service rate: 240 in/hr (6.5 years of service, no maintenance)

Note: City of Olympia has observed (anecdotal) evidence of lower infiltration rates on a sidewalk application; however, no monitoring data have been collected to quantify observations (personal communication Mark Blosser, August 2004).

Pervious pavers: highest initial infiltration rate (new installation): none reported
 lowest initial rate (new installation): none reported
 highest in-service rate: 2000 in/hr
 lowest in-service rate: 0.58 in/hr

Clogging from fine sediment is a primary mechanism that degrades infiltration rates. However, the design of the porous surface (i.e., percent fines, type of aggregate, compaction, asphalt density, etc.) is critical for determining infiltration rates and performance over time as well.

Various levels of clogging are inevitable depending on design, installation, and maintenance and should be accounted for in the long-term design objectives. Studies reviewed in the Porous Paving Research (see Appendix 7) and a review conducted by St. John (1997) indicate that a 50 percent infiltration rate reduction is typical for permeable pavements.

European research examining several permeable paver field sites estimates a long-term design rate at 4.25 inches per hour (Borgwardt, 1994). David Smith from Interlocking Concrete Pavement Institute, however, recommends using a conservative 1.1-inch per hour infiltration rate for the base course (surface intake can be higher) for the typical 20-year life span of permeable paver installations (Smith, 2000).

The lowest infiltration rate reported for an in-service permeable paving surface that was properly installed was approximately 0.58 inches/hour (Uni Eco-Stone parking installation).

Results from the three field studies evaluating cleaning strategies indicate that infiltration rates can be restored. Pervious paver research in Ontario, Canada indicates that infiltration rates can be maintained for Eco-Stone with suction equipment (see Appendix 7: Porous Paving Research). Standard street cleaning equipment with suction may need to be adjusted to prevent excessive uptake of aggregate in paver cells (Gerrits and James, 2001). Washing should not be used to remove debris and sediment in the openings between pavers. Suction should be applied to paver openings when surface and debris are dry.

Street cleaning equipment with sweeping and suction perform adequately on moderately degraded porous asphalt while high pressure washing with suction provides the best performance on highly degraded asphalt (Dierkes, Kuhlmann, Kandasamy and Angelis, 2002 and Balades, Legret and Madiéc, 1995). Sweeping alone does not improve infiltration on porous asphalt.

Water Quality

Research indicates that the pollutant removal capability of permeable paving systems is very good for constituents examined. Laboratory evaluation of aggregate base material in Germany found removal capability of 89 to 98 percent for lead, 74 to 98 percent for cadmium, 89 to 96 percent for copper, and 72 to 98 percent for zinc (variability in removal rates depended on type of stone). The same study excavated a 15-year old permeable paver installation in a commercial parking lot and found no significant concentrations of heavy metals, no detection of PAHs, and elevated, but still low concentrations of mineral oil in the underlying soil (Dierkes et al., 2002).

Pratt, Newman and Bond recorded a 97.6 percent removal of automobile mineral oil in a 780 mm (approximately 31-inch) deep permeable paver section in England. Removal was attributed largely to biological breakdown by microbial activity within the pavement section, as well as adhesion to paving materials (Pratt, Newman and Bond, 1999).

A study in Connecticut compared driveways constructed from conventional asphalt and permeable pavers (UNI group Eco-Stone) for runoff depth (precipitation measured on-site), infiltration rates, and pollutant concentrations. The Eco-Stone driveways were two years old. During 2002 and 2003, mean weekly runoff depth recorded for asphalt was 1.8 mm compared to 0.5mm for the pavers. Table 6.3.1 summarizes pollutant concentrations from the study (Clausen and Gilbert, 2003).

Table 6.3.1 Mean weekly pollutant concentration in stormwater runoff, Jordan Cove, CT.

Variable	Asphalt	Paver
TSS	47.8 mg/L	15.8 mg/L
NO ₃ -N	0.6 mg/L	0.2 mg/L
NH ₃ -N	0.18 mg/L	0.05 mg/L
TP	0.244 mg/L	0.162 mg/L
Cu	18 ug/L	6 ug/L
Pb	6 ug/L	2 ug/L
Zn	87 ug/L	25 ug/L

(Adapted from Clausen and Gilbert, 2003)

In the Puget Sound region, a six-year permeable parking lot demonstration project conducted by the University of Washington found toxic concentrations of copper and zinc in 97 percent of the surface runoff samples from an asphalt control parking stall. In contrast, copper and zinc in 31 of 36 samples from the permeable parking stall—that produced primarily subsurface flow—fell below toxic levels and a majority of samples fell below detectable levels. Motor oil was detected in 89 percent of the samples from the surface flow off the asphalt stall. No motor oil was detected in any samples that infiltrated through the permeable paving sections. (Brattebo and Booth, 2003).

6.4 Vegetated Roofs

Vegetated roofs (also known as green roofs and eco-roofs) fall into two categories: intensive and extensive. Intensive roofs are designed with a relatively deep soil profile (6 inches and deeper) and are often planted with ground covers, shrubs, and trees. Intensive green roofs may be accessible to the public for walking or serve as a major landscaping element of the urban setting. Extensive vegetated roofs are designed with shallow, light-weight soil profiles (1 to 5 inches) and ground cover plants adapted to the harsh conditions of the roof top environment. This discussion focuses on the extensive design.

Vegetated roofs improve energy efficiency and air quality, reduce temperatures and noise in urban areas, improve aesthetics, extend the life of the roof, and reduce stormwater flows.

Extensive green roofs offer a number of benefits in the urban landscape including: increased energy efficiency, improved air quality, reduced temperatures in urban areas, noise reduction, improved aesthetics, extended life of the roof, and central to this discussion, improved stormwater management (Grant, Engleback and Nicholson, 2003).

Companies specializing in vegetated roof installations emerged in Germany and Switzerland in the late 1950s, and by the 1970s extensive green roof applications were common in those countries. In 2003, 13.5 million square meters of green roofs were installed in Germany (Grant et al., 2003; Peck, Callaghan, Kuhn and Bass, 1999; and Peck, Kuhn and Arch, n.d.). While roof gardens are not as prevalent in the U.S., designers in North America are discovering the value of the technology and green

roofs are becoming more common with installations on large buildings and individual residences in Portland, Philadelphia, Chicago, Seattle, and other cities.



Figure 6.4.1 Vegetated roof on the Multnomah County building in Portland, Oregon.

Photo by Erica Guttman

6.4.1 Applications

Initial vegetated roof installations in the 1970s were prone to leaking. New technologies and installation techniques have improved and essentially eliminated past problems. Green roofs can be installed on almost any building with slopes up to 40 degrees and are effective strategies for managing stormwater in highly urbanized settings where rooftops comprise a large percentage of the total impervious surface (Scholtz-Barth, 2001).

6.4.2 Design

Native soils are heavy and would exert unnecessarily heavy loads for an extensive green roof installation, particularly when wet. Extensive roofs utilize light-weight soil mixes to reduce loads. Installations often range from 1 to 6 inches in depth and research from Germany indicates that, in general, a 3-inch soil depth offers the best environmental and aesthetic benefit to cost ratio (Miller, 2002).

While roof gardens can be installed on slopes up to 40 degrees, slopes between 5 and 20 degrees (1:12 and 5:12) are most suitable, and can provide natural drainage by gravity (depending on design, sloped roofs may also require a drainage layer). Flat roofs require a drainage layer to move water away from the root zone and the waterproof membrane. Roofs with slopes greater than 20 degrees require a lath grid to hold the soil substrate and drainage aggregate in place (Scholtz-Barth, 2001).

Vegetated roofs are comprised of four basic components: waterproofing membrane, drainage layer, growth medium, and vegetation. (See Figure 6.4.2 for a typical cross-section of a green roof.)

Waterproof membranes are made from PVC, Hypolan, rubber (EPDM) or polyolifins. Sixty to 80-mil reinforced PVC with heat sealed seams provides a highly durable and waterproof membrane. EPDM seams must be glued and may be more susceptible to leakage. Thermoplastic polyolifins are currently not well tested in the U.S., and U.S. manufacturers use bromides in the manufacturing process as a fire

retardant which may interfere with long-term performance. Asphalt-based roofing material should be covered with high-density polyethylene membrane to prevent roots and other organisms from utilizing the organic asphalt as an energy source (Scholtz-Barth, 2001). Some membranes are not compatible with asphalt-based or other roofing materials. Follow manufacturer's recommendations for material compatibility.

The *drain layer* consists of either aggregate and/or a manufactured material that provides channels designed to transmit water at a specific rate. This layer can include a separation fabric, which with the drainage layer, reduces moisture contact with the waterproof membrane and provides additional protection from root penetration (Peck et al., n.d.).

The *light-weight growth medium* is designed to support plants and infiltrate and store water at a specific rate. The growth medium typically has a high mineral to organic material content and can be a mixture of various components including: gravel, sand, crushed brick, pumice, perlite, encapsulated Styrofoam, compost, and soil (Peck et al., n.d.). Saturated loads of 15 to 50 pounds/square foot are typical for extensive roofs with 1- to 5-inch soil depths (Scholtz-Barth, 2001). Currently, vegetated roofs weighing 15 pounds/square foot (comparable to typical gravel ballast roofs) have been installed and are functioning in the U.S. At 15 to 50 pounds, many roofs can be retrofitted with no or minimal reinforcement. Separating the growth medium from the building perimeter and roof penetrations with a non-combustible material (e.g., gravel) can provide increased protection against spread of fire, easier access to flashing and membrane connections, and additional protection from root penetration (Peck et al., n.d.).

Vegetation is typically succulents, grass, herbs, and/or wildflowers adapted to harsh conditions (minimal soils, seasonal drought, high winds, and strong sun exposure—i.e., alpine conditions) prevalent on rooftops. Plants should be adapted or native to the installation area. Some examples of species include: sempervivum, sedum, creeping thyme, allium, phloxes, and antenaria. (Scholtz-Barth, 2001). Plants can be installed as vegetated mats, individual plugs, spread as cuttings, or by seeding. Vegetated mats and plugs provide the most rapid establishment for sedums. Cuttings spread over the substrate are slower to establish and will likely have a high mortality rate; however, this is a good method for increasing plant coverage on a roof that is in the process of establishing a plant community (Scholtz-Barth, 2001). During the plant establishment period soil erosion can be reduced by using a biodegradable mesh blanket.

A bonus for eco-roofs

The city of Portland encourages the application of eco-roofs in the central city to reduce stormwater runoff. Buildings using eco-roofs can earn bonus floor area (exceeding maximum floor area ratios) depending on the extent of coverage. For example, if the total area of the eco-roof is at least 60 percent of the building's footprint, each square foot of eco-roof earns three square feet of additional floor area.

Flow modeling guidance

See Chapter 7 for flow modeling guidelines for vegetated roofs when using WWHM.

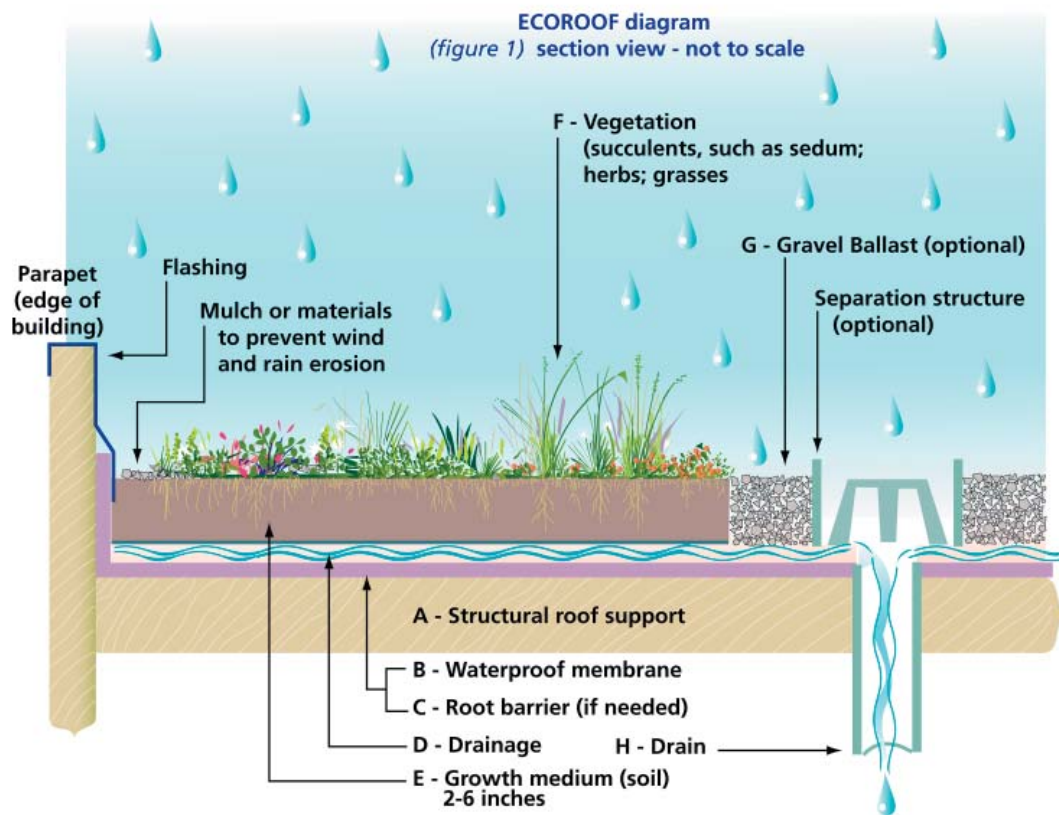


Figure 6.4.2 Cross section of vegetated roof garden.
© Environmental Services,
Portland, Oregon

For a sample vegetated roof specification, see Appendix 9.

6.4.3 Maintenance

Proper maintenance and operation are essential to ensure that designed performance and benefits continue over the full life cycle of the installation. Each roof garden installation will have specific design, operation, and maintenance guidelines provided by the manufacturer and installer. The following guidelines provide a general set of standards for prolonged roof garden performance. Note that some maintenance recommendations are different for extensive versus intensive roof gardens. The procedures outlined below are focused on extensive roof systems and different procedures for intensive roof recommendations are noted.

Schedule

- All facility components, including structural components, waterproofing, drainage layers, soil substrate, vegetation, and drains should be inspected for proper operation throughout the life of the roof garden.
- The property owner should provide the maintenance and operation plan, and inspection schedule.
- All elements should be inspected twice annually for extensive installations and four times annually for intensive installations.
- The facility owner should keep a maintenance log recording inspection dates, observations, and activities.
- Inspections should be scheduled to coincide with maintenance operations and with important horticultural cycles (e.g., prior to major weed varieties dispersing seeds).

Structural and drainage components

- Structural and drainage components should be maintained according to manufacturer's requirements and accepted engineering practices.
- Drain inlets should provide unrestricted stormwater flow from the drainage layer to the roof drain system unless the assembly is specifically designed to impound water as part of an irrigation or stormwater management program:
 - o Clear the inlet pipe of soil substrate, vegetation or other debris that may obstruct free drainage of the pipe. Sources of sediment or debris should be identified and corrected.
 - o Inspect drain pipe inlet for cracks, settling and proper alignment, and correct and re-compact soils or fill material surrounding pipe if necessary.
- If part of the roof design, inspect fire ventilation points for proper operation.

Vegetation Management

- The vegetation management program should establish and maintain a minimum of 90 percent plant coverage on the soil substrate.
- During regularly scheduled inspections and maintenance, bare areas should be filled in with manufacturer recommended plant species to maintain the required plant coverage.
- Normally, dead plant material will be recycled on the roof; however specific plants or aesthetic considerations may warrant removing and replacing dead material (see manufacturer's recommendations).
- Invasive or nuisance plants should be removed regularly and not allowed to accumulate and exclude planted species. At a minimum, schedule weeding with inspections to coincide with important horticultural cycles (e.g., prior to major weed varieties dispersing seeds).
- Weeding should be done manually and without herbicide applications.
- Extensive roof gardens should be designed to not require fertilization after plant establishment. If fertilization is necessary during plant establishment or for plant health and survivability after establishment, use an encapsulated, slow release fertilizer (excessive fertilization can contribute to increased nutrient loads in the stormwater system and receiving waters).
- Intensive green roofs installations require fertilization. Follow manufacturer and installer recommendations.
- Avoid application of mulch on extensive roof gardens. Mulch should be used only in unusual situations and according to the roof garden provider guidelines. In conventional landscaping mulch enhances moisture retention; however, moisture control on a vegetated roof should be through proper soil/growth media design. Mulch will also increase establishment of weeds.

Irrigation

- Surface irrigation systems on extensive roof gardens can promote weed establishment and root development near the drier surface layer of the soil substrate, and increase plant dependence on irrigation. Accordingly, subsurface irrigation methods are preferred. If surface irrigation is the only method available, use drip irrigation to deliver water to the base of the plant.
- Extensive roof gardens should be watered only when absolutely necessary for plant survival. When watering is necessary (i.e., during early plant

establishment and drought periods), saturate to the base of the soil substrate (typically 30 to 50 gallons per 100 square feet) and allow the soil to dry completely.

Operation and Maintenance Agreements

- Written guidance and/or training for operating and maintaining roof gardens should be provided along with the operation and maintenance agreement to all property owners and tenants.

Contaminants

- Measures should be taken to prevent the possible release of pollutants to the roof garden from mechanical systems or maintenance activities on mechanical systems.
- Any cause of pollutant release should be corrected as soon as identified and the pollutant removed.

Insects

- Roof garden design should provide drainage rates that do not allow pooling of water for periods that promote insect larvae development. If standing water is present for extended periods, correct drainage problem.
- Chemical sprays should not be used.

Access and Safety

- Egress and ingress routes should be clear of obstructions and maintained to design standards.

(City of Portland, 2002 and personal communication, Charlie Miller, February 2004)

6.4.4 Cost

Costs for vegetated roofs can vary significantly due to several factors including size of installation, complexity of system, growth media depth, and engineering requirements. Costs for new construction including structural support range from \$10 to \$15 per square foot. Retrofit costs range from \$15 to \$25 per square foot (Portland Bureau of Environmental Services, 2002). While initial installation costs are higher than for conventional roof systems, they are competitive on a full life cycle basis. Vegetated roofs increase the energy efficiency of a building and significantly reduce associated cooling and heating costs. European evidence indicates that a correctly installed green roof can last twice as long as a conventional roof, thereby deferring maintenance and replacement costs (Peck et al., n.d.). The above costs do not include savings on conventional stormwater management infrastructure as a result of reduced flows from a green roof or reduced stormwater utility fees.

6.4.5 Performance

Vegetated roof designs require careful attention to the interaction between the different components of the system. **Saturated hydraulic conductivity**, porosity and moisture retention of the growth media, and **transmissivity** of the drainage layer strongly influence hydrologic performance and reliability of the design (Miller and Pyke, 1999).

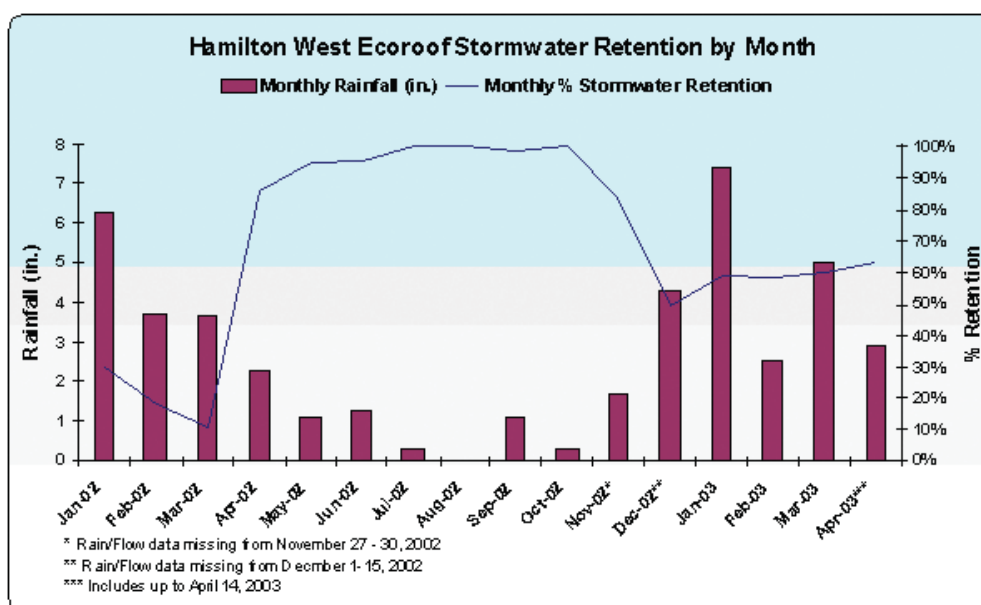
Research in Europe, in climates similar to the northeastern U.S., has consistently indicated that roof gardens can reduce up to 50 percent of the annual rooftop

European research, in climates similar to the northeastern U.S., has consistently indicated that roof gardens can reduce up to 50 percent of the annual rooftop stormwater runoff.

stormwater runoff (Miller and Pyke, 1999). During a 9-month pilot test in eastern Pennsylvania, 14 and 28 square foot trays with test vegetated roof sections received a total of 44 inches of precipitation and generated 15.5 inches of runoff (runoff was negligible for storm events producing less than 0.6 inches of rainfall). The pilot section was 2.74 inches thick, including the drainage layer (USEPA, 2000b).

In Portland Oregon, a 4- to 4.5-inch eco-roof retained 69 percent of the total rainfall during a 15-month monitoring period. In the first January-to-March period (2002), rainfall retention was 20 percent and during the January-to-March (2003) period retention increased to 59 percent. The most important factors likely influencing the different retention rates are vegetation and substrate maturity, and rainfall distribution. The 2002 period was a more even rainfall distribution and the 2003 period more varied with longer dry periods between storms (Hutchison, Abrams, Retzlaff and Liptan, 2003). This supports observations by other researchers that vegetated roofs are likely more effective for controlling brief (including relatively intense) events compared to long-duration storms (Miller, 2002).

Figure 6.4.3 Precipitation and percent stormwater retained on a 4- to 4.5-inch eco-roof, Portland, OR.
Graphic from Hutchison et al., 2003



6.5 Minimal Excavation Foundation Systems

Excavation and movement of heavy equipment during construction compacts and degrades the infiltration and storage capacity of soils. Minimal excavation foundation systems limit soil disturbance and allow storm flows to more closely approximate natural shallow subsurface flow paths. When properly dispersed into the soils adjacent to and in some cases under the foundation, roof runoff that would otherwise be directed to bioretention areas or other LID facilities can be significantly reduced.

Minimal excavation foundation systems can take many forms, but in essence are a combination of driven piles and a connection component at, or above, grade. The piles allow the foundation system to reach or engage deep load-bearing soils without having to dig out and disrupt upper soil layers, which infiltrate, store and filter stormwater flows. These piles are a more “surgical” approach to earth engineering, and may be vertical, screw-augured or angled pairs that can be made of corrosion protected steel, wood or concrete. The connection component handles

the transfer of loads from the above structure to the piles and is most often made of concrete. Cement connection components may be pre-cast or poured on site, in continuous perimeter wall, or isolated pier configurations. For a given configuration the appropriate engineering (analyzing gravity, wind and earthquake loads) is applied for the intended structure. Several jurisdictions in the Puget Sound region have permitted minimal excavation foundations for the support of surface structures, including Pierce and King counties and the city of Olympia.

Minimal excavation foundation systems limit soil disturbance and allow storm flows to more closely approximate natural shallow subsurface flow paths under and around the foundation.

6.5.1 Applications

Minimal excavation foundations in both pier and perimeter wall configurations are suitable for residential or commercial structures up to three stories high. Secondary structures such as decks, porches, and walkways can also be supported, and the technology is particularly useful for elevated paths and foot-bridges in nature reserves and other environmentally sensitive areas. Wall configurations are typically used on flat to sloping sites up to 10 percent, and pier configurations flat to 30 percent. Some applications may be “custom” or “one-off” designs where a local engineer is employed to design a combination of conventional piling and concrete components for a specific application. Other applications may employ pre-engineered, manufactured systems that are provided by companies specifically producing low-impact foundation systems for various markets.

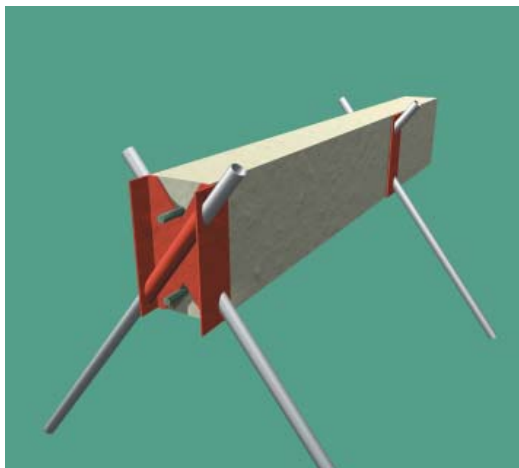


Figure 6.5.1 Typical minimal excavation foundation wall.

Graphic courtesy of Pin Foundations, Inc.



Figure 6.5.2 Building a house on Bainbridge Island using minimal excavation pier system.

Photo courtesy of R. Gagliano

The minimal excavation foundation approach can be installed on A/B and C/D soils (USDA Soil Classification) provided that the material is penetrable and will support the intended type of piles. Typical soils in the Puget Sound region, including silt loams, sandy loams, fine gravels, tight soils with clay content, and partially cemented tills are applicable. Soils typically considered problematic due to high organic content (top soils or peats) or overall bearing characteristics may often remain in place provided their depth is limited and the pins have adequate bearing in suitable underlying soils. These systems may be used on fill soils if the depth of the fill does not exceed the **reaction range** of the intended piles. Fill compaction requirements for support of such foundations may be below those of conventional development practice in some applications. In all cases, both for custom and pre-engineered systems, a qualified engineer should determine the appropriate pile and connection components, and define criteria for specific soil conditions and construction requirements.

Flow modeling guidance

See Chapter 7 for flow modeling guidelines for minimal excavation foundation systems when using the WWHM.

6.5.2 Design

Grading

In general, wall configurations require some site blading or surface terracing to accommodate the wall component itself. The lightest possible tracked equipment should be used for preparing or grading the site. Permeability of some soil types can be significantly reduced even with minimal equipment activity. Consult a qualified hydrological engineer for soil recommendations.

On relatively flat sites, blading should be limited to knocking down the highs and lows to provide a better working surface. Removing the top organic “duff” layer is not typically necessary. A free draining, compressible buffer material (pea gravel, corrugated vinyl or foam product) should be placed on surface soils to prepare the site for the placement of pre-cast or site poured wall components. This buffer material separates the base of the grade beam from surface of the soil to prevent impact from expansion or frost heave, and in some cases is employed to allow the movement of saturated flows under the wall.

Figure 6.5.3 Minimal excavation foundation pins driven with machine-mounted automatic hammer.

Photo courtesy of R. Gagliano



On sloped sites, the soils may be bladed smooth at their existing pitch to receive pier systems, pre-cast walls with sloped bases, or slope cut forms for pouring continuous walls. Grading should be limited to knocking down the superficial highs and lows on the site to provide a better working surface only. This technique will result in the least disturbance to the upper permeable soil layers on sloped sites.

While creating more soil disturbance, the site may be terraced to receive conventional square cut forms or pre-cast walls. The height difference between terraces will be a result of the slope percentage and the width of the terrace itself. The least soil impacts will be achieved by limiting the width of each terrace to the width of the equipment blade and cutting as many terraces as possible. Some footprint designs will be more conducive to limiting these cuts, and should be considered by the architect. The terracing technique removes more of the upper permeable soil layer, and this loss should be figured into any analysis of storm flows through the site. Buffer material as described above should be used on sloping sites regardless of the grading style employed.

Additional soil may remain from foundation construction depending on grading strategy and site conditions. The material may be used to backfill the perimeter of the structure if the impacts of the additional material and equipment used to place the backfill are considered for runoff conditions.

Construction

Minimal excavation systems may be installed “pile first” or “post pile.” The pile first approach involves driving or installing all the required piles in specified locations to support the structure, and then installing a connecting component (such as a formed and poured concrete grade beam) to engage the piles. Post pile methods require the setting of pre-cast or site poured components first, through which the piles are then driven. Pile first methods are typically used for deep or problematic soils where final pile depth and embedded obstructions are unpredictable. Post pile methods are typically shallower—using shorter, smaller diameter piles—and used where the soils and bearing capacities are definitive. In either case, the piles are placed at specified intervals correlated with their capacity in the soil, the size and location of the loads to be supported, and the carrying capacity of the connection component. Soil conditions are determined by geotechnical analysis. Depending on the pile system type, the size or scale of the supported structure, and the nature of the site and soils, a complete soils report including slope stability and **liquifaction** analysis may be required. For other systems a simple statement of soil properties to a limited depth, such as dry unit weight, angle of internal friction, and/or cohesive strength, may be sufficient.

The piles are driven with a machine mounted, frame mounted, or hand-held automatic hammer. The choice of driving equipment should be considered based on the size of pile and intended driving depth, the potential for equipment site impacts, and the limits of movement around the structure. Corrosion rates for buried galvanized or coated steel piling, or degradation rates for buried concrete piling, are typically low to non-existent, and piling for these types of foundations are usually considered to last the life of the structure. Special conditions such as exposure to salt air or highly caustic soils in unique built environments such as industrial zones should be considered. Wood piling typically has a more limited lifetime. Some foundation systems allow for the removal and replacement of pilings, which can extend the life of the support indefinitely.

Figure 6.5.4 Using an automatic hand-held hammer to drive pins.
Photo courtesy of R. Gagliano



Stormwater Dispersion

Where the top or upper levels of soils have been sufficiently retained without significant loss of their permeability and storage characteristics, roof runoff and surrounding storm flows may be allowed to infiltrate without the intervention of man-made conveyance.

Where possible, roof runoff should be infiltrated uphill of the structure and across the broadest possible area. Infiltrating upslope more closely mimics natural (pre-construction) conditions by directing subsurface flows through minimally impacted soils surrounding, and in some cases, under the structure. This provides infiltration and subsurface storage area that would otherwise be lost in the construction and placement of a conventional “dug-in” foundation system. Passive gravity systems for dispersing roof water are preferred; however, active systems can be used if back-up power sources are incorporated and a consistent and manageable maintenance program is ensured.

Garage slabs, monolithic poured patios or driveways can block dispersed flows from the minimal excavation foundation perimeter, and dispersing roof runoff uphill of these areas is not recommended or must be handled with conventional means. Some soils and site conditions may not warrant intentionally directing subsurface flows directly beneath the structure, and in these cases, only the preserved soils surrounding the structure and across the site may be relied on to mimic natural flow pathways.

6.5.3 Performance

From 2000 to 2001 a minimal excavation foundation system was monitored on the Gig Harbor Peninsula. The study site was a two-story, 2300-square foot single-family residence located on a slightly sloped south facing lot with grass surrounding the house and second growth forest on the perimeter. Preparation for the foundation installation involved applying a thin layer of pea gravel directly on the existing lawn to separate the grade beam from the soil, pouring the grade beam from a pump truck, and driving steel pin piling with a hand held pneumatic hammer. The surface organic material was not removed from the construction area. Roof drains fed perforated weep hoses buried 2 to 3 inches in shallow perimeter landscape beds upslope of the house to infiltrate roof runoff and direct it along its natural pre-existing downslope path below the structure.

Soil pits were excavated around and within the foundation perimeter and gravimetric sampling was conducted to measure soil moisture content on a transect from high slope to low slope within the foundation perimeter. Relative humidity in the crawl space below the house was assessed by comparing the minimum excavation foundation system with two conventional foundation crawl spaces in the same area. The soil analysis found 2 to 6 inches of topsoil overlying a medium dense to very dense silty, fine to coarse sand with small amounts of rounded gravel. Bulk density analysis of the upper 6 inches of the soil profile found no indication of compaction after construction (0.89 to 1.46g/cc or below average to average) and the original lawn vegetation had degraded to a fine brown loam under the plastic vapor barrier in the crawl space. Soil moisture readings indicated that roof runoff was infiltrating into the soils under the house and moving downslope through the subsurface soils. At no time was water ponded above the surface, either outside or under the house. The humidity readings in the crawl space under the minimal excavation foundation system were slightly drier than the conventional crawl space, but statistically equivalent, given the variance of the monitoring equipment (Palazzi, 2002).

Additional structures installed on similar systems over the last three years, though not monitored for subsurface flows, have shown similar reductions in soil compaction impacts to the site and foundation perimeter soils.

6.6 Roof Rainwater Collection Systems

Collecting or harvesting rainwater from rooftops has been used for centuries to satisfy household, agricultural, and landscape water needs. Many systems are operating in the Puget Sound region in a variety of settings. On Marrowstone and San Juan islands, where overuse, saltwater intrusion or natural conditions limit groundwater availability, individual homes use rainwater collection for landscaping and potable supplies. In Seattle, the King Street Center building harvests approximately 1.2 million gallons of rainwater annually to supply 60 to 80 percent of the water required for flushing the building's toilets (CH2M HILL, 2001).

6.6.1 Application

Typically, rainwater collection is used where rainfall or other environmental conditions limit the availability of domestic water supply. In a low impact development, rainwater harvesting serves two purposes: water conservation and, most importantly, elimination or the large reduction of the stormwater contribution from rooftops. This practice is particularly applicable in medium to high-density development where the roof is likely to be equal to or greater than the road, driveway, and sidewalk impervious surface contribution. In the medium to high density residential setting with detached single family homes and till soil conditions, the primary LID objective of approximating pre-development hydrology is likely not feasible without reducing or eliminating the stormwater contribution from rooftops through rainwater harvesting applications.

Roof rainwater harvesting systems can be used in residential, commercial or industrial development for new or retrofit projects. The focus of this section is on residential applications. Rainwater harvesting technology is well developed and components readily available; however, system design and construction is relatively complex and should be provided by a qualified engineer or experienced designer.

In a low impact development, rainwater harvesting serves two purposes: water conservation and, most importantly, elimination or a large reduction of the stormwater contribution from rooftops.

6.6.2 Design

Collection systems should be sized according to precipitation inputs, indoor and/or outdoor water needs, and the flow reduction required to approximate pre-development hydrology. Rainwater harvesting should work in concert with other LID practices and therefore reduce the flow reduction requirements from the roof contribution and additional costs of the system.

In the Pacific Northwest the highest precipitation (supply) and lowest demand months are November to May. June through October is relatively dry and demand, driven primarily by landscape needs, is greatest during this period. To collect and remove adequate storm flows during the higher precipitation months and provide a reliable water source, large storage reservoirs or cisterns are required. Where stormwater is a primary incentive for installation and municipal or groundwater supplies are available, the rainwater collection system is installed with, and augmented by, a conventional water source.

Components of a rainwater collection system

Catchment or roof area

The roof material should not contribute contaminants (such as zinc, copper or lead) to the collection system. The National Sanitation Foundation (NSF) certifies products for rainwater collection systems. Products meeting NSF protocol P151 are certified for drinking water system use and do not contribute contaminants at levels greater than specified in the USEPA Drinking Water Regulations and Health Advisories (Stuart, 2001).

Roof materials

- Rainfall present in the Pacific Northwest is surprisingly acidic and will tend to leach materials from roofing material.
- Currently, few roof materials have been tested and the only recommendation for common roof coverings is to not use treated wood shingles or shakes.
- Metal, ceramic tile or slate are durable and smooth, presumed to not contribute significant contaminants, and are the preferred materials for potable supply. Composition or 3-tab roofing should only be used for irrigation catchment systems. Composition roofing is not recommended for irrigation supply if zinc has been applied for moss treatment.
- Lead solder should not be used for roof or gutter construction and existing roofs should be examined for lead content.
- Galvanized surfaces may deliver elevated particulate zinc during initial flushing and elevated dissolved zinc throughout a storm event (Stuart, 2001).
- Copper should never be considered for roofing or gutters. When used for roofing material, copper can act as an herbicide if rooftop runoff is used for irrigation. Copper can also be present in toxic amounts if used for a potable source.

The following general guidelines are used for calculating water production for a rainwater collection system:

- The catchment area is equal to the length times width of the guttered area (slope is not considered).

- One inch of rain falling on one square foot of rooftop will produce 0.6233 gallons of water or approximately 600 gallons per 1,000 square feet of roof without inefficiencies.
- Assume that the system will lose approximately 25 percent of the total rainfall due to evaporation, initial wetting of the collection material, and inefficiencies in the collection process (Texas Water Development Board, 1997). Precipitation loss is the least with metal, more with composition, and greatest with wood shake or shingle.

Roof washers

Roof washers collect and route the first flush away from the collection system. The first flush can contain higher levels of contaminants from particulates settling on the roof, bird droppings, etc. A simple roof washer consists of a downspout (located upstream of the downspout to the cistern) and a pipe that is fitted and sealed so that water does not back flow into the gutter. Once the pipe is filled, water flows to the cistern downspout. The pipe often extends to the ground and has a clean out and valve.

The Texas Rainwater Guide recommends that 10 gallons be diverted for every 1000 square feet of roof (applicable for areas with higher storm intensities) (Texas Water Development Board, 1997). However, local factors such as rainfall frequency, intensity, and pollutants will influence the amount of water diverted. In areas with low precipitation and lower storm intensities such as the San Juan Islands, roof washing may divert flows necessary to support system demands. Additionally, the gentle rainfall prevalent in western Washington may not be adequate to wash contaminants from the roof in the first flush. In this scenario, pre-filtration for coarse material before the storage reservoir and fine filtration (e.g., 5 microns) before disinfection is likely more effective (personal communication Tim Pope, August 2004).

Storage tank or cistern

The cistern is the most expensive component of the collection system. If the system will be used for a potable water source, the tank and any sealants and paints used in the tank should be approved by the Food and Drug Administration (FDA), USEPA or NSF. Tanks can be installed above ground (either adjacent to or remote from a structure), under a deck, or in the basement or crawl space. Above ground installations are less expensive than below ground applications. Aesthetic preferences or space limitations may require that the tank be located below ground, or away from the structure. Additional labor expenditures for excavation and structural requirements for the tank will increase costs of subsurface installations compared to above ground storage (Stuart, 2001). Multiple tank systems are generally less expensive than single tank and the multi-reservoir configurations can continue to operate if one of the tanks needs to be shut down for maintenance.

Cisterns are commonly constructed of fiberglass, polyethylene, concrete, metal, or wood. Larger tanks for potable use are available in either fiberglass for burial or corrugated, galvanized steel with PVC or Poly liners for above ground installations. Tanks should have tight fitting covers to exclude contaminants and animals, and above ground tanks should not allow penetration of sunlight to limit algae growth (Texas Water Development Board, 1997).

Figure 6.6.1 Buried tanks on San Juan Island.
Photo courtesy of Tim Pope



Figure 6.6.2 Collection tanks being installed under deck of a home on San Juan Island.
Photo courtesy of Tim Pope



Figure 6.6.3 Collection tanks hidden under the deck of a home on San Juan Island.
Photo courtesy of Tim Pope





Figure 6.6.4 Storage tank on Lopez Island.
Photo courtesy of Tim Pope

Conveyance

Gutters are commonly made from aluminum, galvanized steel, and plastic. Rainwater is slightly acidic; accordingly, collected water entering the cistern should be evaluated for metals or other contaminants associated with the roof and gutters, and appropriate filters and disinfection techniques installed. Screens should be installed in the top of each downspout. Screens installed along the entire length of the gutter do not prevent most debris from entering the gutter; however, they can complicate cleaning. Leaf guard type gutters will exclude leaves and needles, but do not prevent pollen and dust (the most important contaminant to remove) from entering the gutter.

Unless the tank is elevated sufficiently above the point of delivery, pumps are required to provide acceptable pressure. Municipal water supply pressures are typically between 40 to 60 psi. Pressure tanks are often installed in addition to the pump to prolong the life of the pump and provide a more constant delivery pressure (Stuart, 2001).

Water treatment

Water treatment falls into three broad categories: filtration, disinfection, and buffering.

Filtration

Filters remove leaves, sediment, and other suspended particles and are placed between the catchment and the tank or in the tank. Filtering begins with screening gutter downspouts to exclude leaves and other debris and routing the first flush through roof washers, if compatible with precipitation and water needs (filtration can be incorporated with the roof washer). Types of filters for removing the smaller remaining particles include single cartridges (similar to swimming pool filters) and multi-cartridge filters (Texas Water Development Board, 1997). For potable systems, water must be filtered and disinfected after the water exits the storage reservoir and immediately before point of use.

Disinfection technologies include:

- *Ultra-violet (UV) radiation* uses short wave UV light to destroy bacteria, viruses, and other microorganisms. UV disinfection requires pre-filtering of fine particles

where bacteria and viruses can lodge and elude the UV light. This disinfection strategy should be equipped with a light sensor and a readily visible alert to detect adequate levels of UV light (Texas Water Development Board, 1997).

- *Ozone* is a form of oxygen produced by passing air through a strong electrical field. Ozone kills microorganisms and oxidizes organic material to CO₂ and water. The remaining ozone reverts back to dissolved O₂ (Texas Water Development Board, 1997). Care must be exercised in the choice of materials used in the system using this disinfection technique due to ozone's aggressive properties.
- *Activated carbon* removes chlorine and heavy metals, objectionable tastes, and most odors.
- *Membrane technologies* include reverse osmosis and nano-filtration and are used primarily to filter dissolved materials such as salts or metals.
- *Chlorine* (commonly in the form of sodium hypochlorite) is a readily available and dependable disinfection technique. Household bleach can be applied in the cistern or feed pumps that release small amounts of solution while the water is pumped (Texas Water Development Board, 1997). There are two significant limitations of this technique: chlorine leaves an objectionable taste (which can be removed with activated charcoal); and prolonged presence of chlorine with organic matter can produce chlorinated organic compounds (e.g., trihalomethanes) that can present health risks (Texas Water Development Board, 1997).

Buffering

As stated previously, rainwater is usually slightly acidic (a pH of approximately 5.6 is typical). Total dissolved salts and minerals are low in precipitation and buffering with small amounts of a common buffer, such as baking soda, can adjust collected rainwater to near neutral (Texas Water Development Board, 1997). Buffering should be done each fall after tanks have first filled.

6.6.3 Barriers to Implementation

Two factors present the largest barriers to implementing rainwater harvesting:

1. Regulatory

Authorizing agencies for rainwater collection include the Washington Department of Health, Ecology, and the local jurisdiction. The Department of Health does not recommend rainwater harvesting for potable supplies; however, there are no laws restricting the practice other than appropriate pollutant level criteria for human consumption. The USEPA classifies roof water collection as a surface water system and requires that the water be filtered to federal standards if for potable use. Ecology technically requires that all systems collecting surface water for consumption apply for a water right. Currently, Ecology is not enforcing its authority over roof collection for small systems (e.g., individual homes) (Stuart, 2001). Many local jurisdictions are not familiar with or restrict rainwater harvesting from roofs. In most locations, installing these systems will require special permit considerations.

2. Cost

Roof water harvesting systems can add significant costs to residential construction. Systems that provide adequate storage for reliable indoor use and detain sufficient precipitation require large storage tanks, filtration and

disinfection. In the example provided in Section 6.6.5: Performance, the system (10,000 gallon storage capacity for supplying toilets and clothes washing) added approximately \$8,000/home to the construction costs. Roof water harvesting systems can, on the other hand, provide cost savings. New stormwater management requirements will increase infrastructure costs on challenging sites with medium to high density zoning and soils with low infiltration rates. Much, if not all, of the additional costs associated with a rainwater collection system may be offset by reducing conventional conveyance and pond infrastructure and expenditures. Building owners who use a rainwater harvest system will also reduce monthly expenses by significantly reducing their water bills.

6.6.4 Maintenance

Maintenance requirements for rainwater collection systems include typical household and system specific procedures. All controls, overflows and cleanouts should be readily accessible and alerts for system problems should be easily visible and audible. The following procedures are operation and maintenance requirements recorded with the deed of homes using roof water harvesting systems in San Juan County (personal communication, Tim Pope, August 2004).

- Debris should be removed from the roof as it accumulates.
- Gutters should be cleaned as necessary (for example in September, November, January, and April. The most critical cleaning is in mid to late-spring to flush the pollen deposits from surrounding trees.
- Screens at the top of the downspout should be maintained in good condition.
- Pre-filters should be cleaned monthly.
- Filters should be changed every six months or as pressure drop is noticed.
- UV units should be cleaned every six months and the bulb should be replaced every 12 months (or according to manufacturer's recommendation).
- Storage tanks should be chlorinated quarterly to 0.2ppm to 0.5ppm at a rate of 1/4 cup of household bleach (5.25 percent solution) to 1,000 gallons of stored water.
- Storage tanks should be inspected and debris removed periodically as needed.
- When storage tanks are cleaned, the inside surface should be rinsed with a chlorine solution of 1 cup bleach to 10 gallons water.
- When storage tanks are cleaned, the carbon filter should be removed and all household taps flushed until chlorine odor is noticed. Chlorinated water should be left standing in the piping for 30 minutes. Replace the carbon filter and resume use of the system.

6.6.5 Performance

In 2001, CH2M HILL performed an LID study on a 24-acre subdivision with 103 lots in Pierce County (CH2M HILL, 2001). The site was selected for its challenging conditions—medium density development (4 to 6 dwelling units/acre) located on a topographically closed depressional area and type C soils (USDA soils classification) with low infiltration rates. The study utilized LID principles and practices to redesign the project (on paper only) with the goal of approximating pre-development (forested) hydrologic conditions. LID practices used in the design included reducing the development envelope, minimizing impervious surfaces, increasing native soil and vegetation areas, amending disturbed soils with compost, and bioretention. Hydrologic analysis using continuous simulation (HSPF) was performed to assess the effectiveness of the selected LID practices for achieving the project goal.

The hydrologic simulations of the proposed low impact development design indicated that the goals of the project could not be achieved by site planning and reducing impervious surfaces alone while maintaining four or more dwelling units per acre. The challenging site conditions required that additional LID tools be utilized to approximate forested hydrology. Accordingly, the potential to collect and use rooftop stormwater was considered to reduce surface flows.

A 1,300-sq. ft. impervious footprint was used to reflect the compact, two-story design for the detached single-family homes. At this density the rooftop contributing to the total impervious surface in the development was almost 60 percent. Only non-potable uses such as laundry, toilet, and irrigation were investigated to reduce design costs and regulatory barriers. To estimate the storage volume required for non-potable uses, the amount of water used inside the house was first estimated. The average inside water use for homes that conserve water is approximately 49.2 gallons per person per day (Maddaus, William O., 1987, Water Conservation, American Water Works Association). Table 6.6.1 contains a breakdown of average daily water use per person/day.

Table 6.6.1 Household water use.

Type of Use	Gallons per person per day	Percent of Total*
Showers	8.2	17
Toilets	6.4	13
Toilet leakage	4.1	8
Baths	7.0	14
Faucets	8.5	17
Dishwashers	2.4	5
Washing machines	12.6	26
* The average inside water use for homes that conserve water is approximately 49.2 gallons per person per day		

The project considered using captured rainwater in toilets and washing machines. Stormwater collected from roof runoff may also be used for irrigation but because of the small lot sizes, this use was not factored into the calculation for storage requirements. However, the calculations assume that the storage system will be empty at the beginning of the wet season, so any excess stored water during the summer months should be used for irrigation.

To estimate the amount of storage required, the volume of rainfall from a 1300-sq. ft. surface was plotted over time against curves showing water usage based on a 5-gallon toilet, a 3.3-gallon toilet, a low-flow toilet (1.6 gallon), and a low-flow toilet combined with a washing machine. Monthly average rainfall for Pierce County was used (41.5 inches annually). Although the 5-gallon toilet resulted in the smallest required storage volume, new construction requires the use of low flow toilets, so the storage required for a combination low flow toilet and washing machine was used. This resulted in a required storage volume of approximately 10,000 gallons, or 1,333 cu. ft. Accounting for evaporation and other inefficiencies in the collection process, the 103 houses on the LID site would capture and use approximately 8 acre-ft of water annually.

From a hydrologic standpoint, collecting and using rooftop runoff reduces or removes the roof contribution from the surface water system. Collecting the appropriate percentage of total precipitation can simulate the amount of water that is naturally transpired and evaporated in a forested environment. As a result, the surface water system in the low impact development responds more like a forested system.